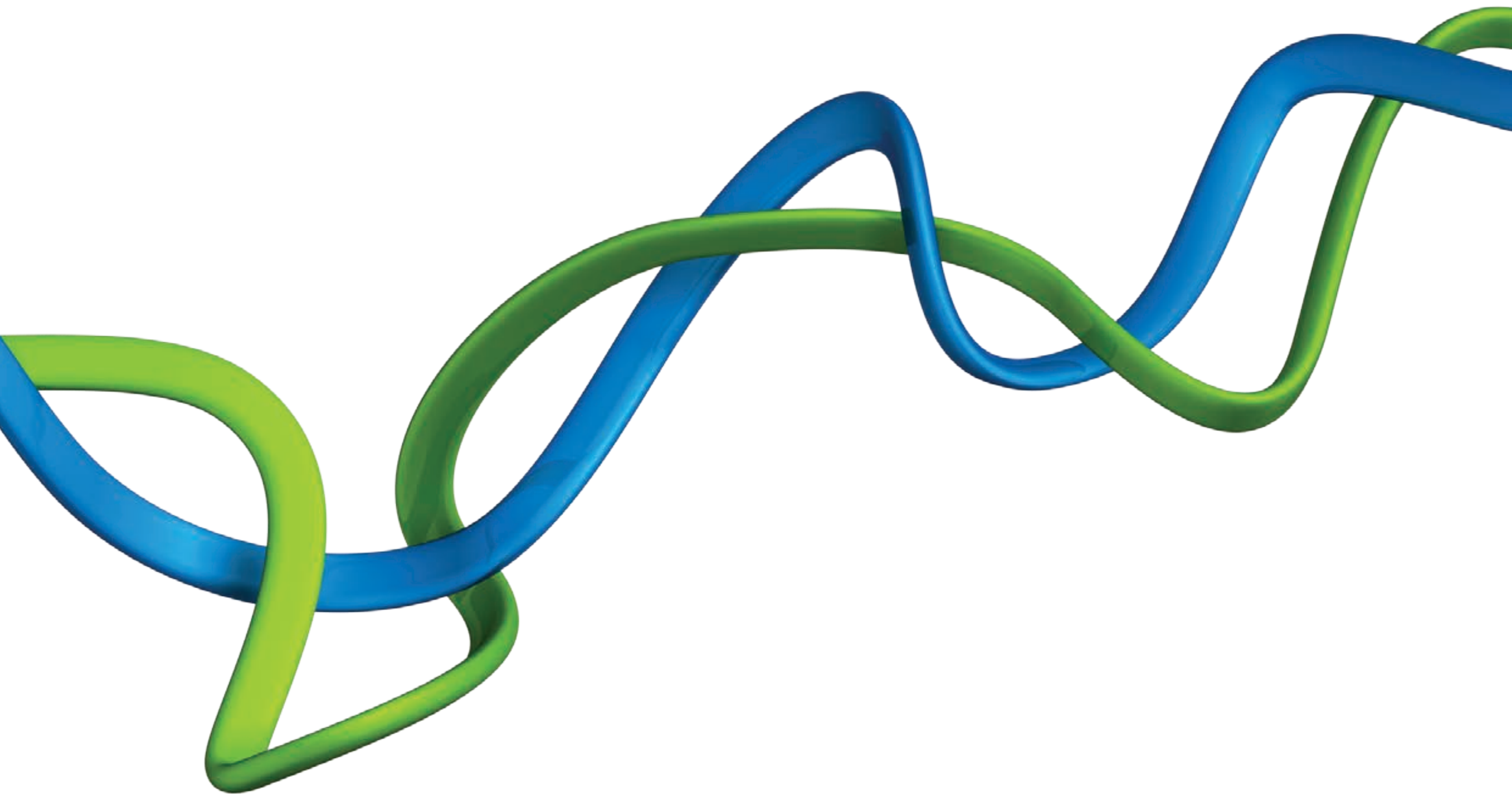
ROYAL ACADEMY OF ENGINEERING

A critical time for UK energy policy

what must be done now to deliver the UK's future energy system

A report for the Council for Science and Technology

October 2015



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Foreword

In 2010, the Royal Academy of Engineering published *Generating the future,* which considered scenarios for the UK's energy system that would meet the emissions targets in the Climate Change Act 2008. In that report, the Academy came to four key conclusions about the decarbonisation of the nation's energy system:

- Fundamental restructuring of the whole energy system will be unavoidable.
- Demand reduction across the whole economy will be essential.
- The full suite of available or credible low carbon energy supply technologies will be needed.
- The scale of the engineering challenge is massive.

That report pointed out the need for a coordinated national strategy to drive the transformation, underpinned by a high degree of whole-systems thinking.

This study, undertaken at the request of the Prime Minister's Council for Science and Technology, considers the future of the energy system that now must deliver against an even greater set of challenges than we considered in 2010. UK energy policy today seeks to deliver solutions to the so-called energy 'trilemma' – the need for a system that is secure and affordable as well as low carbon.

The broader scope of today's challenge brings new uncertainties that add further complexity to policy decision-making. One thing remains certain – the scale of the engineering challenge remains massive and the need for whole-systems thinking remains critical. We hope that the perspectives that the Academy has brought to this analysis will prove useful to those taking forward and integrating energy policy and informative for other readers with an interest in the engineering aspects of this critically important issue.

The challenge is great, but the engineering profession, supported by science and business, is capable of remarkable progress if given the right market and regulatory conditions.

1. Executive summary

1.1 Main conclusions and recommendations

This report was prepared by the Royal Academy of Engineering on behalf of the Prime Minister's Council for Science and Technology. The work was led by a steering group of Academy Fellows and other engineers with expertise in the energy sector. Evidence was gathered through interviews with a wide range of stakeholders and supplementary research.

The main conclusion is that there remain serious risks in the delivery of the optimal energy system for the UK. Substantial investment is needed, largely by the private sector, costs are likely to rise and decarbonisation must be realised across multiple interconnected sectors where the full technical solution is not obvious.

The whole energy system faces massive changes to deliver against all aspects of the 'trilemma' – cost, security and decarbonisation. So far, despite the obvious challenges, the system is on course to meet the targets set by UK and EU, *but only just*, and all the easiest actions have already been taken. Progress in the electricity sector will only get more difficult and there is a serious risk of non-delivery. Moreover, the heat and transport sectors, which account for most of demand and emissions, have yet to be addressed. **Time is of the essence, with decisions taken now affecting what the system will look like in 2030 and beyond**.

The following actions by government are needed as a matter of urgency:

- Undertake local or regional whole-system, large-scale pilot projects to establish real-world examples of how the future system will work. These must move beyond current single technology demonstrations and incorporate all aspects of the energy system along with consumer behaviour and financial mechanisms.
- Drive forward new capacity in the three main low carbon electricity generating technologies – nuclear, carbon capture and storage (CCS) and offshore wind.
- Develop policies to accelerate demand reduction, especially in the domestic heat sector, and the introduction of 'smarter' demand management[1].
- Clarify and stabilise market mechanisms and incentives in order to give industry the confidence to invest.

In undertaking these actions, government must build on partnerships with all industry stakeholders and communicate clearly and honestly with the public the likely consequences of the necessary evolution of the energy system. Each of these points is expanded on below.

It is also worth noting that, **in developing energy policy, the whole system must always be considered**. Electricity, heat and transport, although quite different in their characteristics, are all part of the UK's energy system and are equally important, with complex interactions between them: targets will only be met by addressing all aspects of the system.

[1] We welcome the recently announced Independent Review of Consumer Advice, Protection, Standards and Enforcement for UK home energy efficiency and renewable energy by Dr Peter Bonfield OBE FREng

1.2 Whole system

The energy system must be considered in its entirety, and there is a generally accepted view of how the whole system will develop. Broadly, this consists of decarbonising electricity generation by 2030 through a combination of nuclear, CCS and renewables with some unabated gas[2] to balance the grid and then decarbonising heat and transport, possibly by electrification but with other options still likely to play a role. This supply side decarbonisation needs to be coupled to a general reduction in demand across all sectors, but mainly in the heat sector, with the remaining demand functions being delivered by a variety of decarbonised loads such as heat pumps, combined heat and power (CHP) or electric vehicles, and managed much more intelligently through smart control systems. Energy storage of various types and increased interconnection are also expected to contribute.

There are multiple possible technological solutions but also uncertainties inherent in the evolution of future energy systems. Computer models of various types are used to investigate possible future scenarios. These models reflect some of these uncertainties in their assumptions and sensitivities, but other uncertainties, involving consumer behaviour, engineering realities and business models, are more fundamental and difficult to anticipate through anything other than real-world trials.

Some new technologies could emerge to become unexpectedly significant (such as the recent increase in solar PV brought about by a reduction in cost), and significant steps have been taken in other countries worldwide meaning that there is growing global momentum for innovation and decarbonisation. But large-scale deployment of novel technologies would take decades and the system cannot be planned on promises and aspirations alone.

What is required now is a combination of known technologies, scaled up to unprecedented levels, integrated in smarter ways. Many of these technologies are largely established in principle but have not yet been fully tested as commercial investments and operations. Electrification of heat would be particularly challenging, not least because of the large seasonal variation and the difficulty in managing daily spikes in demand. Replacing gas boilers that currently deliver heat to the majority of homes would also be challenging, as alternatives such as heat pumps are expensive, unfamiliar to consumers and disruptive to retrofit. Achieving such a shift by 2050 would already be difficult as demonstrated by the arguably simpler process of switching to condensing boilers that took over 20 years, as shown in Figure 2.

Electrification of transport would, among other things, require extensive upgrades in the electricity distribution system. Simultaneous electrification of both heat and transport would require a huge increase in total generating capacity beyond what currently exists. Other options are available such as a move to liquid biofuels for aviation and heavy duty vehicles or the use of synthetic gas or hydrogen in the gas grid, but developing these at scale will also present difficulties.

Demonstration and de-risking projects are needed to establish final commercial designs and the business case for large-scale private and public finance investment. **What is required now, to plan the best path forward, are real world demonstrators of how technologies will integrate and, most importantly, how different options will function effectively for all stakeholders**. Pilots must be run at significant regional or

[2] Unabated gas is gas powered generating plant not fitted with carbon capture technology and hence releases CO_2 into the atmosphere.

local scale – encompassing domestic, business and industry consumers and covering all aspects of the energy system, building on the smaller or single-technology demonstrations carried out to date.

International case studies must also be taken into account. Direct replication may not always be viable, but it would be wise to learn as much as possible from work done outside the UK.

Failure to carefully plan the development of the whole energy system will result, at best, in huge increases in the cost of delivery or, at worst, complete failure to deliver.

1.3 Supply

While consideration of the whole system is vitally important, the most immediate concern is to **maintain supply in the electricity system and ensure that new capacity is being built**. Decarbonisation of the electricity system remains a central pillar of all credible future scenarios but uncertainty over the past few years while market reform was completed has resulted in serious underinvestment. **Government now needs to allow the new Electricity Market Reform mechanisms to bed in**. Developers and investors need time to work with the new system in order to reduce financial risks and compete to lower costs. Particular focus needs to be given to the three main technologies that can deliver low carbon electricity at scale:

- **Nuclear** – as a secure, baseload source of low carbon electricity, nuclear power is essential. The UK's current fleet of nuclear reactors is increasingly relying on extensions to its scheduled end of life and no new plant has yet received a final investment decision. Much good work has been done by government to initiate a new build programme but, despite this, progress remains worryingly slow and if construction does not begin soon, delivery will be put at serious risk. The number of possible developers is limited and new reactor designs are proving challenging to deliver, mainly for commercial and financial reasons. At least three possible independent build programmes are possible, and **at least two need to be underway by the mid-point of this administration just to keep pace with closures**. Government policy has been successful to date in encouraging interest in the UK's nuclear new build programme. Maintaining policy stability is important, but, beyond that, success of the current generation of new build projects is to a large extent in the hands of the developers rather than requiring further policy intervention. However, government is encouraged to consider whether any alternative policies beyond those currently being followed might help increase the capacity of nuclear power with particular consideration given to smaller reactors that are easier to finance. In addition, support from government is needed across the whole nuclear research and innovation landscape in order to revitalise the UK's position at the forefront of global developments.
- **Offshore wind** – with the UK already leading Europe with more than half of total installed capacity[3], offshore wind offers the best opportunity for large-scale renewable generation. Recent decisions to end new onshore wind subsidies have dented confidence in all wind investment in the UK, so it is vital to **press ahead with Round 3 developments** to secure investment, establish supply chains and let technical knowledge and economies of scale make offshore wind cost competitive. The UK also has the opportunity to establish a lead in technical advances such as in HVDC cabling and power systems[4].

[3] *www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-European-Offshore-Statistics-2014.pdf* (p.10)

[4] *www.raeng.org.uk/news/news-releases/2015/july/artemis-intelligent-power-wins-macrobert-award-uk*

- **Carbon capture and storage (CCS)** – unlike nuclear and offshore wind, CCS is still to be proved commercially at scale, but like nuclear it has the potential to deliver secure, low carbon electricity and, in many scenarios, it is seen as a critical technology. The technical challenges are understood but costs are not, and in the UK no full-scale demonstration plant has yet started construction. Government has made £1bn of grants available. **Two projects must take advantage of that funding and begin construction**. If they are operational by early 2020s, the UK could contribute to the world market in this technology, which is already developing in North America and China. If they are not, decarbonisation of the electricity system will be at serious risk.

Maintaining security of supply is essential. The capacity margin has been tightening recently, leading to serious concern as expressed in a previous Academy report[5]. Subsequent measures, including interim balancing services and the capacity mechanism, are intended to address this issue but government needs to ensure that these measures will be sufficient to maintain the high level of service expected by UK domestic and business customers. This will require focus in three main areas:

- Ensure sufficient new dispatchable, low carbon energy generation, particularly nuclear and CCS, as noted above, but also biomass. This will complement the variable renewables that cannot be relied on to generate at all times to match demand. It remains to be seen if the capacity mechanism is able to deliver such new generating capacity.
- Ensure that demand side responses, storage and interconnections are fully able to participate in the new capacity mechanism, the first round of which was dominated by generating capacity[6].
- Ensure that wider system characteristics such as inertia, reactive power and frequency control, normally delivered by traditional thermal generation, are not adversely affected as the system evolves.

Failure to do so will risk interruptions in supply leading to significant economic impacts and costly short-term fixes and compromise the drive for decarbonisation.

1.4 Demand

Demand side measures are as important as the supply side. They can either seek to reduce overall levels of demand or more effectively manage demand, primarily by shifting demand to match supply. If well implemented, demand side measures can deliver a more efficient, lower carbon, cost-effective system with the same level of service for lower bills – a win-win situation. But, in reality, they can be difficult to implement. Large-scale, regional or local pilot schemes, as recommended in Section 1.2, are critical to understanding how to unlock the potential of demand side measures.

The biggest immediate wins are to be found in the domestic heat sector but success has proved elusive despite repeated government initiatives. Urgent action is required in the following areas:

- ensuring that energy efficiency measures in buildings deliver on expectations
- focus on retrofitting existing buildings
- delivering benefits to the consumer and tackling fuel poverty.

[5] *GB electricity capacity margin*, RAEng 2013 *www.raeng.org.uk/publications/reports/gb-electricity-capacity-margin*

[6] *www.gov.uk/government/uploads/system/uploads/attachment_data/file/391622/t4_cm_auction_2014.pdf*

Success will depend on learning lessons from successful initiatives both in the UK and abroad, building up a skilled workforce, understanding the motivations of all stakeholders and developing the best technologies for all situations. Further details can be found in Section 6.1.

Transport energy demand can be reduced through more efficient drive technologies such as electrification (already well underway on the railway system) but the biggest changes are not expected before 2030. The main aim for any transport policy should be to reduce emissions over the full life cycle of the vehicles through a fully integrated transport system.

In terms of electricity demand, there is much to be gained for both system operators and consumers from a greater degree of demand management. The next significant development will be the introduction of smart meters but these are just one necessary component of a 'smart grid' that is still some way off. Much more work is needed to understand better the potential of demand management in the electricity sector and ensure a reasonable return on the significant investment that will ultimately be paid for by consumers. As noted in Section 1.3 , in the immediate short term, effort is needed to bring through demand side responses into the capacity mechanism and to learn how demand can effectively be included in markets traditionally designed for supply (this is equally true for electricity storage). In the medium term, more research is needed to assess how real-time, dynamic demand management will function best, providing a fair balance of benefits and costs between utilities and consumers, without which participation levels will be low or customers will lose out on potential savings. In addition, more needs to be known about how demand management will affect fuel poverty and more general issues of equity.

1.5 Government/industry relations

Government policy drives the development of the energy system, but in the UK's privatised system it is industry that will deliver the assets on the ground. **Substantial investment is needed and current investment capacity is fragile**. The UK is still viewed favourably by investors but possibly less so than a few years ago. For example, in the last year, the UK has dropped four places to eleventh in EY's renewable energy country attractiveness index[7] and recent policy changes for support mechanisms are likely to have further reduced investor confidence across all energy sectors. Money is available but often through companies recycling capital or forming consortia to deliver large-scale, high capital projects that bring with them their own risks. What is most important is consistent, sustained policy and cross-party support from government, particularly in the following areas:

- clarity on the future of mechanisms defined in the Electricity Market Reform
- clarity on the size of the Levy Control Framework and how this will be allocated in terms of volume and capacity
- timely completion of the Competition and Markets Authority energy market investigation
- a clearly articulated and cohesive public research and innovation support programme led by DECC.

[7] Renewable energy country attractiveness, EY, September 2015 index *www.ey.com/Publication/vwLUAssets/RECAI-45-September-15-LR/$FILE/RECAI_45_Sept_15_LR.pdf#page=35*

Establishing confidence in the energy market is essential. Without sustained confidence, there is a real risk that the companies making investment decisions will decide against the UK in favour of other countries in what is a global market for energy infrastructure. This would result in a lack of generating capacity, risks to security of supply and decarbonisation targets being missed.

Equally important is recognition that, in the UK's private sector but publicly regulated system, **government and industry must act in partnership**. The public faces potentially expensive and difficult changes that will be much harder to accept if both government and industry do not work together. It is critical that the public is engaged with honestly and clearly about the reasons for the changes and their likely impacts. The Academy recognises the challenge of engaging in open communication on issues that are so politically charged and commercially sensitive. **However, failure to work together by all stakeholders may be the single biggest risk for delivery of the future energy system**.

1.6 Time is critical

In policy terms, 2030 may seem far away (three parliamentary terms) but in engineering terms, with long lead times, the need to secure planning consents, time required to build, and operational lifespans and capital return periods that run into decades, **the future is closer than it might seem**.

The scale of the transformation required is huge, so decisions need to be made and actions sustained. The big system decisions cannot be allowed to drift. The various options need to be tested and a sequence of deliverables defined. **Decarbonisation of the electricity system is the immediate goal and the actions set out in Section 1.1 need to be acted on immediately**. But in addition, by 2030, the country needs to be realising, or at least on a track for, wide-scale deployment of low carbon heating and transport. The design and testing of low carbon heating and transport solutions need to start now, given the long lead-time (10 years or more) required for their development and commercialisation.

2. Background

This study was undertaken at the request of the Prime Minister's Council for Science and Technology to consider the future evolution of the UK's energy system in the short to medium term. It aims to consider how the system is expected to develop across a range of possible trajectories identified through modelling and scenarios, matching these against what reality might hold as seen from the perspective of those working in the sector and the insights of the working group of Academy Fellows who led the study.

The point in time under consideration centres around 2030. This point was chosen as midway between where we find ourselves today and the more distant 2050 that is the most common long-term target for legislation and many of the scenarios. The primary audience for the findings of the report is decision makers within government who have the responsibility of driving the agenda forward at the strategic level. Those implementing the new system in industry should also find the report useful. No system can function without thought for the end users, so the report aims to be informative for other readers with an interest in the engineering aspects of this critically important issue.

The focus of the report is to offer insight into the risks and uncertainties relating to delivery of the solution to the energy 'trilemma' – a secure, affordable, low-carbon energy system. This is a well-trodden path, with much analysis already undertaken. In carrying out this study, no further original quantitative research was undertaken; instead, existing work was reviewed and interviews conducted with relevant stakeholders. The working group of Academy Fellows and other leading engineers who led the study distilled this information and used their own expertise and experience to produce a set of key messages and recommendations. In particular, emphasis has been given to those aspects of the current system that represent the greatest risk of failure.

3. The trilemma

3.1 Definition of the trilemma

The ‘trilemma’ has become the standard way of assessing energy systems, highlighting three distinct objectives that have to be met but which are often in tension with one another. Although this is a relatively simplistic way of describing a complex system, it remains a useful way to assess delivery of the key objectives. The following describes the standard formulation of the trilemma and some of the shortcomings that need to be kept in mind:

- **Cost**: system affordability is a basic requirement but it is very difficult to provide definitive figures because of a number of inherent uncertainties. Differences in the capital and operating costs of technologies make direct comparisons hard, costs for developers can be quite different from costs for customers and volatility in global commodity prices make forecasts uncertain. The study group’s main concern was overall system costs for the end user but consideration is also given to availability of investment capital.
- **Security**: reliability of energy supplies is a complex issue with many aspects covering resilience of primary fuel supplies, the various transmission and distribution networks and real-time generation of electricity. The study focused on the electricity system and its ability to deliver power when and where it is needed while maintaining system stability.
- **Decarbonisation**: this can be broadened to include environmental sustainability, taking in, among other things, other greenhouse gases, pollutants and material constraints. However, the study group concentrated on decarbonisation targets, particularly progress towards the 80% carbon reduction by 2050 expressed in the Climate Change Act 2008.

While these are the key concerns that should currently occupy decision-makers, it is important that the dynamics and interdependencies between the three aspects of the trilemma are recognised. **Each pillar of the trilemma is important – ignoring any one will result in failure across the system**.

Figure 1 illustrates the current state of the trilemma in the electricity system and gives an indication as to the relative risk of failure for each pillar. The risks indicate how potential failure in one of the pillars can potentially lead to increased stress on the other two pillars. Similar issues will arise across all parts of the energy system.

Security and decarbonisation are seen as having medium risk levels although security is considered to be more at risk following National Grid reporting that de-rated capacity margins would have dropped to 1.2% in winter 2015/16 without the procurement of additional electricity reserves[8] . Even so, specific legislation and market mechanisms are in place to address both of these pillars, although more still needs to be done to ensure continued system security and keep decarbonisation on track – any complacency could easily push either into the ‘red’.

[8] *www2.nationalgrid.com/UK/Industry-information/Future-of-Energy/FES/Winter-Outlook/*

Figure 1: Current state of the trilemma in the electricity system

Cost is seen as critical, given that most low carbon options require market support mechanisms of the order of £100/MWh or more – much higher than current wholesale prices, and thus likely to increase the unit price of electricity. Increased efficiency may offset this, but other uncertainties exist concerning the Levy Control Framework and externalities such as the price of fossil fuels. Cost will be the most vulnerable if security and decarbonisation remain non negotiable for government[9].

3.2 Whole system evolution – the consensus view

A review of various energy system models showed a very general common consensus on the expected pathway for meeting the challenge of the trilemma. In very broad terms this can be described as:

- significantly decarbonise the electricity system by 2030 through a mixture of nuclear energy, CCS and renewables with some unabated gas generation remaining for balancing
- then accelerate the decarbonisation of heat and transport sectors, most likely through electrification but also possibly through alternative energy vectors such as hydrogen or synthetic fuels

[9] *https://decc.blog.gov.uk/2015/07/09/clear-priorities-for-decc/*

- retain a centralised national transmission system but make the distribution system more dynamic or 'smart'.

Although there is still scope for significant variation in the details within this overall pathway (and more significant deviations), most of the industry stakeholders interviewed by the study group saw it as the expected trajectory. For this reason, this report concentrates mainly on the critical issues with the delivery of this overall pathway.

3.3 What models really are: limitations and usefulness

Modelling and scenarios provide a powerful tool for analysing future energy systems and policy interventions. They have made a significant contribution to understanding the theoretical feasibility and affordability of a range of decarbonisation trajectories but they are not a crystal ball into the future. It is important to understand some common limitations:

- **Assumptions**: model outputs are dependent upon a pre-imposed envelope of constraints, such as: meeting energy service demands, carbon constraints, forecasts of GDP and its energy intensity, and fuel prices or technology hurdle rates. Models are reliant on the strength and availability of this input information, all of which is subject to high degrees of uncertainty that could result in very different outputs. To account for this, models are run for a range of sensitivities using the best available knowledge, but it should always be remembered that the primary use of models is to test sensitivities within a given envelope of set constraints.
- **Political and social will**: the imposed constraints in fact represent a proxy for a huge amount of political will and broader social consensus that are not explored or tested within the models, only assumed. Models do not explain how such will and consensus are to be generated and maintained; they simply rely on them as a driver. Yet, in reality, this driver is likely to be the most critical and most challenging prerequisite of the low carbon transition.
- **Failure not an option**: in most cases, although not all, models will always give an answer. Costs will be optimised, supply will be assured or sufficient investment will be available. In reality, however, failure is always an option.

In general, while models allow testing of the sensitivity of a system (acting within an envelope of macro assumptions) to different sets of decisions and developments, they are unable to provide a detailed blueprint for optimisation going forward.

3.4 Uncertainties

In addition to the issues noted above in Section 3.3, the following are examples of more specific uncertainties that some or all of the various types of models face:

- **Large numbers of small changes**: parts of the system that are made up of large units or components such as electrical generating plant are, in many respects, easier to deal with. What is less certain are technologies that involve large numbers of individuals making personal choices. Examples include personal transport or heating options or small-scale embedded generation such as solar PV. These are contingent on factors that can flip suddenly from unfavourable to favourable, resulting in deployment going from low levels to high growth in a short space of time. For example, electric vehicles have shown slow growth to date, but should the cost reduce significantly and they become popular, numbers could increase dramatically. Models can show such behaviour, but predicting precisely when this might happen is difficult, though critical for the operation of the system.

- **Infrastructure**: at present, one of the main uncertainties that many modellers mention is the future use of the gas grid. Decarbonisation targets would suggest that, at some point, the gas grid will become unsustainable. However, it is a significant national asset, providing the majority of buildings with their heating fuel, and would be a major undertaking to replace. There is also the possibility that the gas grid could be used in the future for synthetic fuels or hydrogen made from excess renewable electricity.

  More generally, infrastructure can cause problems for models. In cost terms, when priced over their full lifetime, national infrastructure tends to be relatively cheap, as it lasts a long time. But in practical terms, the upfront costs of replacing old or installing new infrastructure are very high and that does not take into account the levels of upheaval required or the risk of stranded assets.

- **Distributed generation**: up to now, the distribution system has only had to deal with relatively predictable levels of one-way demand. Increasingly, generation is being embedded into the distribution system, largely in the form of solar PV, but also combined heat and power (CHP). Although each unit is relatively small, in aggregate they already generate represent significant amounts (over 550,000 solar PV installations totalling 1.7 GW by the end of Q1 2015[10]) and this is likely to increase considerably. This is another example of the 'large number of small changes' issue mentioned above that could have particular technical impacts on the system and is very difficult to model with precision.

- **Business models**: models mostly assume that market structures will remain broadly the same and that the main players will continue to control the market. It is possible that this will not be the case, and that new players and business models could disrupt the system in unpredictable ways. There are already hints of this with companies such as Google/Alphabet getting involved in heating controls. This could bring advantages with increased competition and new ways of thinking but will be very hard to predict.

All the uncertainties noted above, in fact, represent fundamental issues within the energy system. The fact that models are unable to deal with them is not a surprise and a reminder that models will not provide all the answers.

In order to overcome the uncertainties, real-world demonstration and de-risking projects are needed to establish final commercial designs and the business case for large-scale private and public finance investment. All aspects of the energy system must be considered and assessed against all three pillars of the trilemma in order to understand how technologies will integrate and, most importantly, how different options will function effectively for all stakeholders. Pilots must be run at significant regional or local scale – encompassing domestic, business and industry, building on the smaller or single technology demonstrations carried out to date.

The main message to take from this section of the report is that the energy system must be planned in its entirety. Failure to adequately control any one of the pillars of the trilemma will result in increased stress on the other two pillars with cost being the most at risk. Fundamental uncertainties within the energy system mean that careful planning and testing of the whole system is required and a better understanding of how new technologies will scale-up and integrate together in the real world.

[10] www.gov.uk/government/statistics/energy-trends-section-6-renewables

4. Timelines

A key engineering reality of delivering the future energy system is the pressing timeframe for action. Failure to act in a timely manner will result in failure within the system, whether this is missing carbon reduction targets, significant cost increases, failures of supply (inadequate security) or a combination of all three. Recognising this, and that such negative outcomes are not necessarily captured by the models (see Sections 3.3 and 3.4), is of critical importance.

Figure 2 illustrates the kinds of engineering timescales involved and how they interact with political and market factors. Historic comparators are also shown to provide real-world examples of significant technological changes. A number of lessons can be drawn from Figure 2:

- **Historical comparators**

  Each of these examples shows that an initial period of planning and testing is required that, typically, lasted around 10 years. Roll-out to maturity could then take decades; the length of time depending mainly on the size of the technologies involved, their typical replacement rate and stringency of associated regulatory measures and government policy.

  Government policy is normally required for implementation, either through regulation or financial support. In most cases, millions of individual properties or people are affected but tangible benefits are provided.

- **Replacement rates of current technologies**

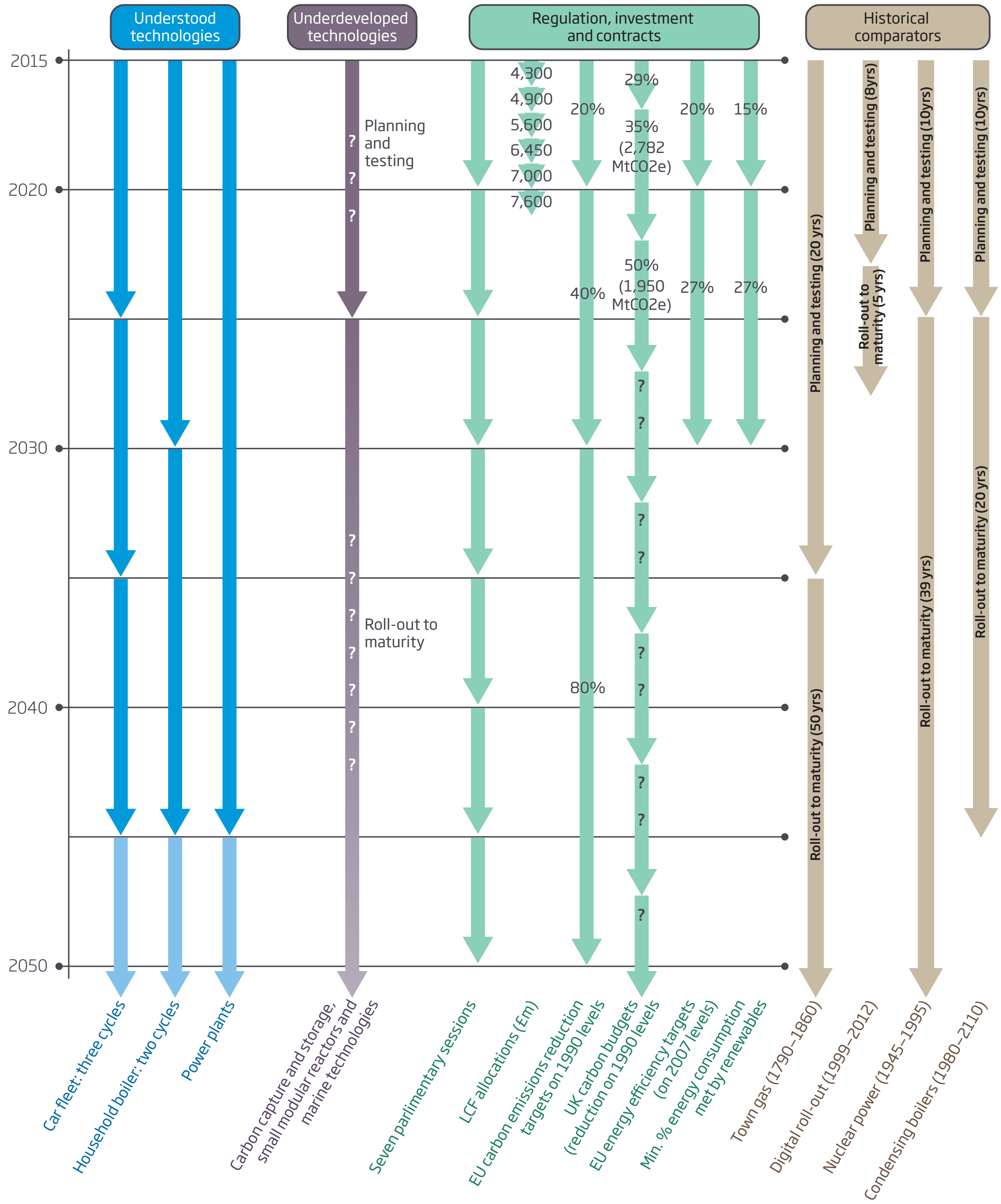
  The lessons from the historical cases relate directly to current technologies. Any new technology will also require the initial decade-long period of planning and testing. The rate at which it could then be rolled out would depend on the typical replacement rate of the technology. So, changes in the road vehicle fleet are likely to happen relatively quickly; but even then, there will only be around three to four replacement cycles by 2050. Changes in heating will take longer, with only about two cycles by 2050 and in the power sector, plant built now will last well into the 2040s.

- **Political and regulatory cycles**

  Sitting alongside the timescales of technical roll-outs are examples of political cycles and targets. There will only be three parliamentary sessions up to 2030. By this time, the electricity system will need to have been largely decarbonised and plans must be in place for the decarbonisation of heat and transport. Emission reduction targets are in place, but as the question marks show, the exact trajectory is yet to be defined. Of greater concern are the cases where the arrows stop. Obviously, not all policies can be set for decades into the future. But they must, wherever possible, fit into the technical timescales of planning, testing and investing.

The main message to take from this assessment of timelines is that political decisions must take account of long technical and investment timescales. Large-scale changes in the system must be carefully planned and based on solid evidence, ideally from community- and regional-scale pilot schemes. Clear, credible and costed strategies need to be laid down for industry to deliver against.

Figure 2: Timelines



5. Supply side

The following chapter considers the range of technologies available on the supply side of the energy system. However, as noted in Section 3, it is the whole system that is important. In order to illustrate this, Appendix 1 analyses how different combinations of generating capacity in the electricity system affect the overall performance in relation to the trilemma.

5.1 Nuclear

With a strong new build programme, it is possible that nuclear capacity in 2030 could be as high as 15 GW. However, if new build stalls, it could be as low as 5 GW which would be a major concern. A key early warning sign for the low end of the range will be if only one final investment decisions has been taken on new plant before 2020[11].

Responses from interviews suggest that the UK is seen as being committed to new Gen III nuclear and that much good work has been done with regards to generic design assessments and sites for new build. Difficulties arise from the very high capital costs required and the small number of potential developers (presently, EDF, NuGen and Horizon). With only three developers in the frame, there is less opportunity to drive down costs through competition for CfDs.

It is also possible that, should all three developments move forward, the UK could again face the situation of building different types of reactor without the opportunity of learning lessons and gaining economies of scale.

Beyond the current raft of Gen III reactors, small modular reactors (SMRs) might offer an alternative with easier financing (smaller units, shorter build time) but as yet there are no commercially available options and therefore unknown £/MWh performance.

Significance	High – currently the only large-scale, low carbon, baseload generation in the UK
Likely range by 2030	5 – 15 GW With the current fleet reaching the end of life and only three possible developers, exceeding the top of the range would be highly unlikely
Risks	Critical – long planning and build times mean progress needs to be pushed, ideally to establish two or more build programmes with the necessary financing

[11] A final decision on Hinkley C is expected very soon although plans to start generating by 2023 have been delayed: *www.bbc.co.uk/news/business-34149392*

5.2 Carbon capture and storage (CCS)

Most models suggest a significant contribution from CCS. Its main advantage is to enable the continued use of fossil fuels while avoiding most of the carbon emissions. Ultimately, the potential of negative emissions through the use of CCS with biomass is also an option. However, this technology remains largely unproven at commercial scale and significant questions remain over its technological and economic scalability[12].

There is a pressing need to deliver the government's two planned competition projects by 2020 and provide clarity on relevant Contracts for Difference (CfD) design[13]. Investments will need to be front-loaded and the construction of pipeline networks coordinated in the early stages of infrastructure development, as these will be valuable, long-term shared assets. Indeed, the beginnings of a CO_2 transportation network that allows follow-on projects would perhaps be the most important development from any demonstration projects.

There are no serious concerns over the technical aspects of CCS as all the individual elements of the process have been demonstrated. The main challenge will be economic, whether based on a price for carbon through the EU Emissions Trading System (ETS) or other support mechanism for storing carbon, a way needs to be found to make CCS economically viable, and this will only begin to happen when the technology is fully demonstrated at scale.

Significance	High – huge potential in allowing baseload, low carbon generation
Likely range by 2030	0–5 GW The top of this range is challenging and will require an infrastructure network for transport and storage to be implemented
Risks	Critical – needs demonstration plants to prove technical and economic viability

5.3 Offshore wind

Wind energy is the most mature of the various renewable technologies, although solar PV has recently made significant advances in terms of cost reduction. The opinion of most of those interviewed in the industry is that, despite the lower costs of the technology, opportunities for significant increases in onshore wind will be limited and that, for the UK, offshore wind offers the only remaining option for large-scale wind development. Recent government announcements reinforce this opinion: announced in the Queen's Speech 2015 was the intention to remove the need for the Secretary of State's consent for any large (over 50MW) onshore wind farms and make the local planning authority the primary decision maker for all onshore wind consents in England and Wales[14] as well as a commitment to end new subsidies for onshore wind farms[15].

There are still uncertainties around the viability and cost of deep offshore wind turbines as well as clarity needed on both the Levy Control Framework (LCF) levels (which need to be sufficient to allow developers to benefit from economies of scale) through the 2020s and on remaining CfDs. The recent auction for CfD allocations showed the advantage of competition with strike prices of below £120/MWh[16] – well on the way to being competitive with onshore wind or nuclear although it should be recognised that the

[12] The first commercial scale CCS power plant is now operational in Canada run by SaskPower: *http://saskpowerccs.com/ccs-projects/boundary-dam-carbon-capture-project/*

[13] *www.gov.uk/uk-carbon-capture-and-storage-government-funding-and-support*

[14] *www.gov.uk/government/uploads/system/uploads/attachment_data/file/430149/QS_lobby_pack_FINAL_NEW_2.pdf*

[15] *www.gov.uk/government/news/changes-to-onshore-wind-subsidies-protect-investment-and-get-the-best-deal-for-bill-payers*

[16] *www.gov.uk/government/statistics/cfd-auction-allocation-round-one-a-breakdown-of-the-outcome-by-technology-year-and-clearing-price*

viability of these prices will only be confirmed if the projects are actually implemented and the cost reductions are repeated in subsequent auctions. Until a full-scale Round 3 development is completed, there remains uncertainty over the full potential of offshore wind.

Significance	High – UK well-placed to deploy at significant scale
Likely range by 2030	20–40 GW Build rates of over 2GW per year are achievable but require proof of viability of deep-water Round 3 developments and industry confidence for long-term support
Risks	Moderate – continued support to help establish supply chain

5.4 Biomass

Most low carbon scenarios envisage a significant role for bioenergy in 2050, accounting for around 15–20% of primary energy demand. By 2030, the use of bioenergy is predicted to be more modest, but could still account for 5–10% of primary energy, primarily in the transport sector through fuel blending, commercial sector heating demand, and co-firing in electricity generation (ideally with CCS). Significant questions remain around the viability and sustainability of bioenergy at scale, particularly in terms of where the biomass is sourced and how to ensure proper monitoring and certification of supply chains and replanting regimes. There are also other uses for the land, such as food or raw material production that will compete with increased biomass use for energy production.

Work is required within the EU to develop supply chains and the monitoring and certification of their sustainability. Decisions will also be needed in relation to the trajectory for biomass out to 2050 in order for investments in infrastructure to be made.

Significance	Medium – marginal but significant contribution, particularly for certain uses such as heavy duty transport and co-firing
Likely range by 2030	Uncertain
Risks	Moderate – work needed to determine potential scale of sustainable supplies

5.5 Other renewables

A number of other renewable or low carbon types of generation could contribute to the electricity system in the coming years. These include solar PV, wave, tidal, geothermal, hydroelectric and energy from waste.

Solar PV: this has seen substantial cost reductions, contributing growing amounts of capacity in recent years (5.4GW by the end of 2014[17]). Installations tend to be small-scale domestic or business uses that have taken advantage of government subsidies and falling prices. This is an example of the phenomenon of large numbers of small changes occurring quickly, noted in Section 3.4, and can be particularly problematic as the output is hidden from the system operator in the distribution system, more often measured as negative demand rather than as generation. There can also be local network issues arising because of a clustering of solar PV in certain regions such as South West England.

[17] *www.gov.uk/government/statistics/energy-trends-section-6-renewables* (table 6.1)

Solar PV has certain characteristics that both help and hinder system operators. It is relatively predictable, with output only during daylight hours and the level depending on the amount of cloud cover. This correlates reasonably well with demand at certain times of day, particularly when demand is at its lowest from around midnight to 6am. But the output from solar PV will always be zero at times of peak electricity demand on winter evenings and will therefore not contribute to the capacity margin at that time. That does not mean that the electricity generated will not be useful; but it will be important to better understand how it could be integrated into the system effectively through demand management and storage. Lessons can certainly be learned from other countries such as Spain and Germany where levels are already much higher than the UK.

Tidal: Planning of large scale tidal schemes such as Swansea Bay is underway, with government entering negotiations on a possible CfD[18] and a GW scale contribution from this or other schemes is feasible by 2030. Cost does not look attractive in the medium term, but the developers point to the very long life of such plants over which the average cost will approach that of other generation types.

A contribution from tidal stream turbines is also possible at reasonable cost. The major test of this will be the current development of the MeyGen array off North Scotland[19].

Wave: At this stage, wave power seems unlikely to make a significant contribution by 2030 as a result of the unfavourable economics that decades of development have as yet been unable to resolve.

Hydroelectric, geothermal and energy from waste: these will have limited impact in the medium term. They are all relatively mature and well understood and should be exploited wherever appropriate. But at the national UK energy system level, they will always be marginal, although they may be important contributors in specific regions and localities.

5.6 Fossil fuels

Beyond CCS, there are additional issues relating to fossil fuels that will be important as the energy system evolves:

- **Shale gas and tight oil**: much has been made about the possibility of developing an onshore oil or gas sector in the UK through the use of modern directional drilling techniques and high volume, high pressure hydraulic fracturing, commonly known as 'fracking'. This has transformed the energy system in the US, resulting in it recently switching from being a net importer of primary fuel supplies to being a net exporter. Extensive possible reserves have been identified in the UK: British Geological Survey has central estimates of 4.4 billion barrels of oil-in-place in the Weald basin and 1.3 trillion cubic feet of gas-in-place in the Bowland Shale[20]. But these are 'in-place' estimates and until more exploratory drilling occurs, it is unclear what proportion of these reserves would be recoverable and at what price.

  Assuming that the resources turn out to be economically viable, Chapter 4 demonstrates that new developments take many years to reach full potential and so it is unlikely that shale gas or oil will have a significant impact on the UK energy system by 2030. This is particularly true given the level of public opposition to fracking that will probably delay development.

[18] *www.gov.uk/government/uploads/system/uploads/attachment_data/file/416330/47881_Budget_2015_Web_Accessible.pdf* (p.41)

[19] *www.meygen.com/*

[20] *www.bgs.ac.uk/shalegas/*

Even then, the addition of shale gas or oil is unlikely to have a major impact on the evolution of the UK's energy system. The UK already has secure and diverse supplies of hydrocarbons from multiple sources. Indigenous shale gas or oil would simply become another piece of the global supply chain of a commodity whose use should, in the UK, be constrained by climate change regulation. It could have an impact on broader economic factors such as balance of trade and tax revenues and could also increase the security of primary fuel supplies, but it is not expected to substantially impact on the large-scale make-up of the UK energy system.

- **The price of oil and gas**: the last year has seen a large and unexpected fall in the price of oil. Brent Crude dropped from almost $120 per barrel in July 2014 to below $50 per barrel in January 2015, and has since fluctuated between around $70 and $50 per barrel. Similar falls have occurred in all global oil markets and have now precipitated falls in the price of gas. There are multiple political and economic reasons for this fall in prices, but few analysts anticipated it, and the fall in prices has already had considerable impacts across the whole global energy sector.

  For the UK, this is both good and bad news. Lower oil prices mean cheaper petrol and diesel prices at the pump, helping to relieve pressure on the cost of living for many and providing a boost to the economy. But the lower prices have also hit the North Sea oil and gas industry hard, especially as the cost of extraction there is among the highest in the world.

  It is difficult to predict what will happen to the price of oil, but the industry has been in similar positions many times before and is likely to ride out this current price readjustment. What this demonstrates is that the energy system in the UK cannot be seen in isolation from the rest of the world and is always subject to external influences beyond both the control and foresight of those designing and operating the system.

  ETI ESME analysis suggests that the major energy system design impact of prolonged lower oil and gas prices is to increase the likely (long-term) installed capacity of gas plant coupled with CCS for power generation. There is minimal system design change to 2030.

5.7 Storage and interconnectors

Interconnection: the UK has only limited levels of interconnection in its electricity grid accounting for approximately 5% of electricity demand[21]. There are two interconnectors with the European grid to France and the Netherlands with a joint capacity of 3.2 GW and two to Ireland (one to Northern Ireland and one to Republic of Ireland) with a joint capacity of about 1 GW. These interconnectors are high-voltage DC point-to-point links. They are not synchronised to the grid and operate as distinct entities in the market, flowing in whichever direction the price is higher. In the current market, the Dutch and French connectors mainly import electricity to the UK, and the Irish ones generally export from Great Britain.

A number of new interconnectors is planned, seven of which have signed contract agreements to be commissioned by 2020 with two (Belgium and Norway) moving ahead. It is not clear how many more of the proposed schemes will be realised.

[21] *www.gov.uk/government/uploads/system/uploads/attachment_data/file/447632/DUKES_2015_Chapter_5.pdf* (table 5.2)

Within the GB grid system, increased levels of transmission are also important with major upgrades and new lines planned, particularly from north to south to connect up Scottish renewables with demand centres in the South East and reinforcements for new, bigger nuclear plant.

In general, better interconnection within the GB grid and with other European grids is an important way of increasing the diversity of the whole system which, in turn, improves resilience. With more variable renewable generation on the system, there is the assumption that wider interconnection will smooth out some of the variations in supply. Evidence suggests that periods of low output for UK wind energy will still coincide with similarly low output from Europe[22], but the main advantage is seen in the increased diversity that comes from connecting to a larger system with multiple sources of generation. This is undoubtedly true to an extent, but uncertainties remain as to how the interconnectors will operate at times of stress, given that they are independent entities that simply respond to market signals and that there is no guarantee that the systems at both ends of the interconnector will not be at stress simultaneously.

Storage: some forms of energy or primary fuels are much more amenable to storage than others. Fossil fuels are very easy to store: coal can just be piled in a heap, oil in tanks and even gas can be stored and transported easily (the UK currently has relatively small amounts of gas storage compared to Europe but, for decades, the North Sea has acted as a huge gas storage facility). Biomass or biofuels can also be stored but need more care than fossil fuels.

Electrical energy is much more difficult to store, at least at grid scale. There is much interest and research in the field at present as cheap, grid-scale storage would solve many of the problems of variable renewables. Many technical options are available, with pumped hydro and compressed air systems offering the most potential for large-scale electricity storage and a number of battery options in development, either aggregated together or distributed in homes or vehicles. Estimates of how much storage capacity might be on the system in the future are highly uncertain, given that the scope for increasing the capacity of mature technologies like pumped storage is limited for economic and environmental reasons and most of the other options are at an earlier stage of development. The Low Carbon Innovation Coordination Group report on Energy Networks & Storage[23] has a central scenario of 9.1 GW capacity (43 GWh electrical energy over the year) by 2020 rising to 27.4 GW (128 GWh) by 2050. This is relatively modest, given that current electrical demand is in the order of 360,000 GWh per year, but the estimates are subject to a high degree of uncertainty. The success of electrical storage will depend as much on finding ways to integrate storage into a market designed primarily for traditional thermal generation and renewables as it will on overcoming the technical challenges.

Thermal storage could also play an important role in the future system as alternatives are sought to replace gas as the primary source of low-grade heating. Low cost thermal heat stores coupled with electric heat pumps offer one possible solution but it remains to be seen if these can cope with the large seasonal variations of heat loads and if they can provide the level of service expected by consumers at competitive prices.

[22] *www.raeng.org.uk/publications/reports/wind-energy-implications-of-large-scale-deployment* (section 7.2)

[23] www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/electricity_networks_storage/

6. Demand side

Influencing demand is as important as the supply side and heat and transport are even more important than electricity with demand playing a significant role in both.

Action can be taken to impact demand in two ways:

- **Demand reduction**: measures to reduce the overall level of demand will result in less primary fuel or generating capacity. This in turn will mean lower carbon emissions, a smaller and therefore cheaper system and lower utility bills. If achieved through energy efficiency, there is no reason why a reduction in demand should mean a reduction in the level of service.
- **Demand management**: controlling demand to better match energy supplies, mainly to reduce peaks in demand or take advantage of surpluses in supply. This can help to optimise the use of energy system assets and avoid local network issues as well as delivering better value for consumers.

Demand side measures can, effectively, deliver a more efficient, lower carbon, cost-effective system with the same level of service for lower bills – a win-win situation. This can be done either through more efficient technology or infrastructure, better interconnection and systems management or behaviour change. Unfortunately, the demand side is more prone to the uncertainties noted in Section 3.4, particularly the fact that what is needed are a very large number of small changes. Understanding how to effectively deliver such changes in a way that works for industry, system operators and consumers is a challenge.

6.1 Heat

The biggest immediate wins are to be found in the domestic heat sector, but success has proved elusive despite repeated government initiatives, most recently the Green Deal and the domestic Renewable Heat Incentive. Urgent action is required to radically improve the thermal efficiency of the UK's building stock. The recent removal of funding by government for the Green Deal is understandable given its poor performance but new policies must be put in place quickly. The Academy welcomes the Independent Review of Consumer Advice, Protection, Standards and Enforcement of energy efficiency and renewable energy measures in existing properties being undertaken by Dr Peter Bonfield OBE FREng[24]. Areas that the review should focus on include:

- **Energy efficiency measures in buildings**: such measures often do not deliver the theoretical savings. Addressing this design/performance gap needs to be a priority for government through improving models, research into product performance, ensuring competence of suppliers and installers, understanding of occupier behaviour and better enforcement of building regulations.
- **Retrofitting existing buildings**: new build is important but the vast majority of buildings that will be around in 2050 have already been built. A concerted effort on research and innovation is needed in this area. A greater willingness to use regulatory measures to drive a minimum level of energy-efficient refurbishment needs to be

[24] *www.gov.uk/government/publications/bonfield-review-terms-of-reference*

developed, possibly by extending some of the policies and minimum legal requirements that currently apply only to new build. Innovative solutions that go beyond the legal requirement may be achieved through the deployment of voluntary industry standards to promote higher performance.

- **Technical, process and financing innovation**: in the medium term, this will be needed to deliver net-zero-energy retrofit as a one hit solution for UK buildings as with, for example, the Dutch "Energiesprong" model. New build properties also need to move immediately to a net-zero-energy requirement. Again, the use of voluntary industry standards may accelerate adoption of a net-zero-energy requirement, where this is seen as a market differentiator rather than a matter of legal compliance.
- **Skills**: ensure that there is a sufficient and well-trained workforce to install and maintain efficient low carbon domestic and commercial heating systems.
- **Learning lessons**: lessons must be learned from initiatives that are succeeding, especially large-scale city schemes in the UK and abroad that coordinate actions across multiple stakeholders. Lessons can also be learned from less successful initiatives.
- **Commercial drivers vs consumer needs**: there is a need to understand the commercial drivers of the construction industry and the needs of consumers. Schemes that conflict with either of these will fail.
- **Understand new technologies**: different technologies will work best in different locations and for different consumers, and this needs to be explored. Heat pumps, heat networks, biomass and others will all have their place.
- **Community energy efficiency schemes**: there is considerable scope to explore the opportunities and potential of different models of community level engagement.
- **Fuel poverty**: a clear focus needs to be maintained on addressing fuel poverty, levels of which are closely tied to affordability of domestic heating.

6.2 Transport

In the transport sector, demand can be reduced by a number of means. Engines can be made more efficient, vehicles can be made to require less energy to drive them or people's overall usage or mode of transport can be modified. Future alternative means of powering vehicles such as electrification are discussed in Section 7.1.1 but, for all types of vehicles there is still much that can be done to reduce demand through design. Vehicle weight can be reduced through the introduction of new materials or smaller vehicles. This can and should be driven by legislation to which this sector is used to responding. These would, however, only ever be marginal, though worthwhile, improvements.

Much more could be achieved through changes in usage. Utilisation of the current car fleet is very low, with most cars sitting idle for most of the time. As new technologies and companies enter the market, this ownership model may change. Changes will be largely incremental but could ultimately prove disruptive should one particular technology be found to be particularly successful. Overall, in the timeframe to 2030, the transport sector is not expected to see wholesale changes, but by then a clear pathway towards decarbonisation based on real world evidence should have been developed. The main aim for any transport policy should be to reduce emissions over the full life cycle of the vehicles through a fully integrated transport system. It should also be noted that an effective national transport system is vital to the health of the economy.

6.3 Electricity and smart grids

Legislation has done much in the area of electricity demand, for example, in driving energy-saving light bulbs and more efficient appliances, but there is much more that can be done. As with the transport sector, progress in this area is best achieved through legislation. The most immediate area where a difference is expected on demand is through the introduction of smart meters for electricity and gas, leading ultimately to a 'smart grid'. The programme for the roll-out of smart meters is well underway but has encountered a series of delays to resolve issues around functionality, security and data access. The roll-out programme represents a significant expense that will ultimately fall on the consumer. It is important that this programme is completed as soon as possible and in such a way that the benefits are felt by all parties.

While smart meters are well understood, the concept of a 'smart grid' is less well defined. The concept is clear enough: a fully dynamic, two-way system that allows end users to both use and generate power and to manage their demand at a component level through time-of-use tariffs and automatic control. Its potential is enormous for both the user and the system operator but trials to date have often shown only a modest reduction in demand[25].

In theory, users will be able to either reduce demand or shift their demand to times when it is cheaper or more convenient. At the system level, the ability to shift demand could contribute significantly to system security and the integration of various types of generation. However, serious questions remain on whether the needs of the user and the system are compatible or conflicting and how much demand could be shifted over what timescales. Smart meters are only the first stage and they will only have a meaningful impact when they are connected up to devices and appliances. Even then, there are currently only a limited number of electrical appliances whose usage could be altered significantly. It will only really be when heat and transport loads are managed alongside electricity demand that the full potential of the smart grid will be realised and that is still some way off.

For all aspects of demand, a deeper understanding of the relationship between technologies and actual behaviour is vital. This will only be gained through trials and pilot schemes, as recommended in Section 1.2. These will need to move beyond individual technologies to assess the performance of full systems including power, heat and transport at the community level.

[25] *www.gov.uk/government/uploads/system/uploads/attachment_data/file/407542/2_ELP_Domestic_Energy_Consumption_Analysis_Report.pdf*

7. System issues beyond 2030

7.1 Electrification of heating and transport

While the consensus view described in the section 3.2 generally assumes the decarbonising of a centralised electricity grid by 2030, with broadly conventional technologies remaining for transport and heating, it assumes a much more radical technological change in the provision of heat and transport between 2030 and 2050. There are significant uncertainties associated with this and significant impacts can be expected for the electricity grid.

7.1.1 Transport

Deep decarbonisation in private passenger transport beyond 2030 implies major technological reconfiguration, as opposed to incremental change. The three main options are fully electric vehicles (EVs), biofuels and hydrogen.

Electrification is already well underway on the railway system, but large scale EV roll-out could result in an overall doubling of current electricity demand levels (averaged over the year) and would require substantial upgrades in the distribution system. It would also require a step change in battery performance, in terms of storage capacity, cost, lifetime and recharging time. The time taken to roll out such innovations should not be underestimated. If hydrogen were to meaningfully contribute, significant improvements in cost and performance would need to be achieved, especially in the area of storage, where optimising energy density, weight and cost will be crucial. Finally, if biofuels are to contribute, they will have to overcome concerns over the scalability of sustainable supplies.

All technological options also require the development of new infrastructure and supporting legislation. The motor industry would not commit to a mass production of alternative vehicles without clarity and commitment on this issue. Given fleet turnover times and for the first steps on infrastructure to be ready to be taken in a timely fashion, the period until 2030 is critical for encouraging the development of options and a strong, long-term policy signal about the requirements for low carbon transport post-2030. It should be noted that options may not necessarily rely on the individual ownership of cars, as is already the case for young Londoners.

Beyond private passenger transport, other areas of transport, such as long haul and heavy duty transport remain the most difficult to decarbonise and will likely rely on the establishment of sustainable biofuels or hydrogen.

Electrification of personal transport remains the most likely option. There are potential system benefits because, despite increasing the demand of electrical energy, the demand can be shifted to some extent to periods of low demand or high output of renewables, although there is a limit to how much the demand could be shifted. The batteries could even be used as a store of electricity. Sensible management through smart grids and time-of-use tariffs could therefore increase system control options and limit the necessary increases in generating capacity. But this will only happen through careful testing and trials to understand how drivers' behaviour impacts on the system.

7.1.2 Heat

Heat will be even more difficult to decarbonise than transport as multiple government initiatives, all of which have underperformed, have shown. Most heating technologies such as boilers have a lifespan up to twice as long as that of vehicles, and the majority of the buildings that will be in use in 2050 already exist today. Again, there are multiple options, including electric heat pumps, CHP units, district heating and even hydrogen. But, unlike vehicles, fitting different technologies means disruption to people's living space and potentially a very different quality of living. There are also multiple different types of user across both business and domestic sectors and one solution is unlikely to satisfy all.

Improved energy efficiency is paramount. Although the rebound effect might mean that reduced heating bills might encourage people to keep their environments warmer, needing less energy to provide the same amount of heat will benefit the user in lower bills and the system in lower demands. However, despite this obvious driver, improving the thermal efficiency of our housing stock has proved more difficult than expected. There are a variety of reasons for this, including the 'hassle factor' of renovations, financial packages that do not benefit the right people, and installations of technologies that do not meet expectations resulting from an inadequately skilled workforce. Legislation is a major driver in the construction sector and any new minimum legal requirements for new buildings must be rigorously enforced by the appropriate authorities. Retrofitting solutions to existing stock is even more important. In both new build and retrofitting options, the use of voluntary standards that promote progressively higher levels of performance through contractual (procurement) routes should be explored as a versatile, market-driven solution and alternative to regulation.

In terms of the system, the seasonal variation in heating demand will be particularly problematic, especially for forms of energy – such as electricity – that are not easily stored. In winter, demand for heating is currently around three times the peak electricity demand but close to zero in the summer. Coping with this via the electricity grid without new, large-scale storage systems will be especially challenging. Ultimately, if the thermal efficiency of the building stock is improved to a sufficient level, this might become manageable. And, if hot water demand comes to dominate, that could be used as a storage system. But, without ongoing and more significant pilot schemes, effective solutions will not be found.

Appendix 1
System characteristics at the extremities of credible scenarios

Interviews with industry stakeholders revealed insights into possible deployment ranges for electricity generation technology types by 2030. Interviewees tended to describe optimistic outcomes, contingent upon various engineering and political factors being favourably aligned, as well as acknowledging the possibility of more pessimistic outcomes.

Two scenarios were developed for this report, one of which combines the optimistic, high deployment end of the ranges suggested in all technology types; the other combines the pessimistic, low deployment end of the ranges across all technologies. The installed capacities of low carbon generating types represent the high and low end of ranges discussed in interviews[26]; the installed capacity of CCGT was subsequently added to ensure the generation mix sustained a de-rated capacity margin of close to 5% – a reasonable margin for a secure system.

Demand is assumed to be relatively stable up to 2030 and both scenarios use peak load (57GW) and annual demand figures (380TWh) that are similar to 2013 levels and broadly in line with National Grid's future scenarios. Details of assumptions and calculations are given below. Although these are reasonable assumptions for the period up to 2030, they do mask the unprecedented challenge posed by the significant changes in electrical demand that will arise if heat and transport loads are switched to the electricity system.

The resulting two scenarios – high deployment and low deployment – are intended to be credible representations of an envelope of possible future systems, rather than to indicate what might happen in reality. The purpose is to assess, in the broadest terms, the implications to the electricity system and highlight potential risks for each pillar of the trilemma. The implications for individual technologies are assessed in Section 5.

The metrics considered are:

- CO_2 intensity – expected to be around 50 gCO_2/kWh if Climate Change Act targets are to be met.
- The implied load factor for the required amount of CCGT plant – currently already quite low at 30%, anything lower will make it difficult for the CCGT to be profitable without significant capacity payments.
- The de-rated capacity margin if there is no wind – if negative this would imply insufficient generating capacity to meet peak demand in low wind conditions.
- The percentage of output from the wind fleet that would result in a zero de-rated capacity margin – the lower this is the more likely it would be that peak demand is not met.
- The percentage output from the wind fleet that would mean minimum demand is met assuming full output from the nuclear fleet – this would result in over supply and the lower this figure the more likely it is to occur.
- Total installed generating capacity – 86.2 GW in 2013.

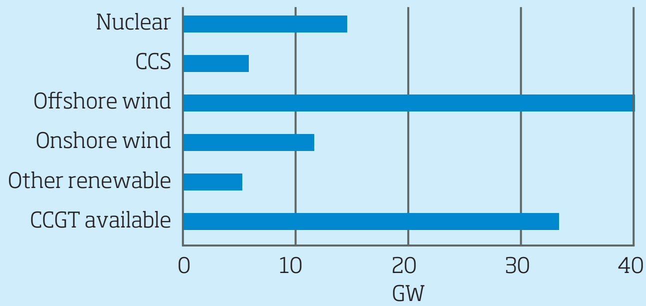
[26] Note: solar PV has seen substantial increases over the past year but has not been included in these representative scenarios. While there is a significant likelihood of material capacity being added over the next decade, without the widespread introduction of associated local storage and matching with demand management systems, all the system issues we identify would still be expected to occur

In reality, the system is much more complicated and will include interconnection, storage and demand side responses. Other choices may also be made: for example, there may still be some coal generation rather than all CCGT. These scenarios therefore simply highlight where problems might arise given different development paths. Reality would likely turn out to be somewhere in between these two scenarios, but it is clear that all systems will face challenges

High deployment scenario

The high deployment scenario below sees deployment of all the main types of low carbon generation at the limit of what is seen as plausible. This, in itself, is high risk as it is uncertain that it could be achieved, particularly for nuclear and CCS.

Installed capacity



De-rated capacity margin (%)	5.0
CO_2 intensity (gCO_2/kWh)	23.1
Implied load factor of CCGTs (%)	8
De-rated capacity margin if no wind (%)	-13.3
% output of wind which gives zero de-rated capacity margin	14.6
% output of wind which hits minimum demand assuming full output from nuclear	9.6
Total installed capacity (GW)	**110.5**

- **Carbon**

  Carbon intensity well within acceptable target range.

- **Cost**

  Costs could be high under this scenario. While the total installed capacity is 110 GW, low load factors of renewables mean additional CCGT capacity is needed to raise the de-rated capacity margin. However, this arrangement forces low load factors for CCGTs, an average of only 8%. Such low load factor plant would require capacity payments to remain open despite limited running hours. There would also be occasions when the combined output of wind, in addition to non-flexible nuclear, could exceed minimum demand. This would trigger constraint payments, adding to costs. Assuming full output of nuclear, wind output of around 10% would be sufficient to exceed minimum demand.

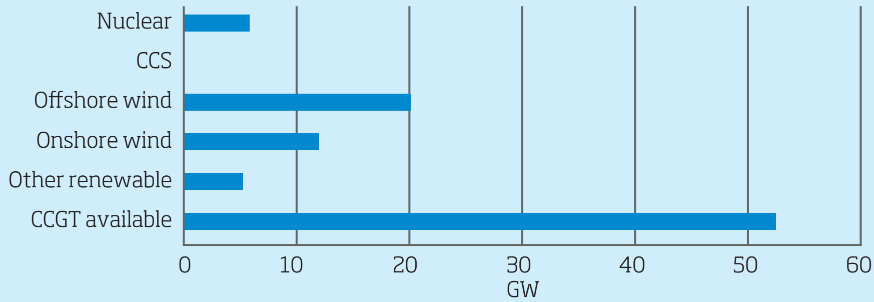
- **Security**

  The de-rated capacity margin would hit zero if wind output dropped to 15% of its total nameplate capacity of 52 GW. If winter peak demands coincided with a less than 15% wind output, additional back up, storage, demand side response, or contribution from interconnectors would be needed.

Low deployment scenario

This scenario sees under-deployment across all types of low carbon generation. The obvious risk here is failure to meet decarbonisation targets, but some additional system issues also occur.

Installed capacity



De-rated capacity margin (%)	5.1
CO_2 intensity (gCO_2/KWh)	234.0
Implied load factor of CCGTs (%)	48
De-rated capacity margin if no wind (%)	-6.1
% output of wind which gives zero de-rated capacity margin	10.9
% output of wind which hits minimum demand assuming full output from nuclear	46.9
Total installed capacity (GW)	**95**

- **Carbon**

  Pessimistic but plausible assumptions on deployment of low carbon generation technologies result in missing the range of carbon intensity required in 2030 by some distance.

- **Cost**

  The total cost would be expected to be lower for this scenario. The total installed capacity is 95 GW, resulting in a higher load factor for CCGTs, of 48%. Occasions when wind combined with full output from nuclear exceeded minimum demand would also be rarer. Wind output would have to exceed 46% before constraint payments were triggered.

- **Security**

  The de-rated capacity margin would hit zero if wind output dropped to 10% of its total rated capacity of 32 GW suggesting that if peak winter demand coincided with less than 10% wind output, additional back up, storage, demand side response, or contribution from interconnectors would be needed.

The two scenarios above illustrate how all future systems will face challenges relating to the trilemma. The scenarios presented are simplistic representations of the system and in reality there are a number of additional levers that could be used to resolve issues. These include storage, interconnection and demand management.

In general, security of supply can always be achieved through interventions even over relatively short time periods, but, if these are not managed carefully, they will increase costs unnecessarily. However, if enough low carbon generation is not built in a timely manner, it would be difficult to rectify that situation easily.

Calculations for scenarios

High deployment

Technology	Installed cap (GW)	DR capacity factor	DR Capacity (GW_DR)	DRCF no wind	DRC no wind (GW-DR)	Av. Annual LF	Annual output (TWh)
Nuclear	15	0.81	12.15	0.81	12.15	1	131.4
CCS	5	0.88	4.4	0.88	4.4	1	43.8
Offshore wind	40	0.2	8		0	0.4	140.16
Onshore wind	12	0.2	2.4		0	0.3	31.536
Other renewable	5	0.88	4.4	0.88	4.4	0.3	13.14
Total low carbon	**77**						**360.0**
CCGT available	33.5	0.85	28.475	0.85	28.475	1	293.46
CCGT as used						0.08	22.1
Total installed cap	**110.5**						

Total CO_2 (g)	8.8×10^{12}
CO_2 intensity (gCO_2/KWh)	**23.1**
DR capacity margin	**5.0**
DR capacity margin no wind	**-13.3**
% output of wind which gives zero DRCF	**14.6**
% output of wind which hits minimum demand assuming full output nuclear only	**9.6**

Low deployment

Technology	Installed cap (GW)	DR capacity factor	DR Capacity (GW_DR)	DRCF no wind	DRC no wind (GW-DR)	Av. Annual LF	Annual output (TWh)
Nuclear	5	0.81	4.05	0.81	4.05	1	43.8
CCS	0	0.88	0	0.88	0	1	0
Offshore wind	20	0.2	4		0	0.4	70.08
Onshore wind	12	0.2	2.4		0	0.3	31.536
Other renewable	5	0.88	4.4	0.88	4.4	0.3	13.14
Total low carbon	**42**						**158.6**
CCGT available	53	0.85	45.05	0.85	45.05	1	464.28
CCGT as used						0.48	223.6
Total installed cap	**95**						
Total CO_2 (g)							8.9×10^{13}
CO_2 intensity (gCO_2/KWh)							**234.0**
DR capacity margin							**5.1**
DR capacity margin no wind							**-6.1**
% output of wind which gives zero DRCF							**10.9**
% output of wind which hits minimum demand assuming full output nuclear only							**46.9**

Total system demand (PJ)	1,376	(Source: MARKAL LC_ED)
Total system demand (TWh)	382.1152	
CCGT carbon intensity (gCO_2/kWh)	400	(Estimate)
Peak system demand (GW)	57	(2013 max)
Min system demand (GW)	20	(2013 min)

De-rated capacity factors (DRCFs) from Ofgem 2013 Capacity Assessment

Appendix 2
Working group

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Dr Martin Grant FREng, WS Atkins plc

Dr Keith MacLean, Chair of UKERC advisory Board, formerly Director, SSE

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Note: **Professor John Loughhead OBE FREng** was originally on the working group but stepped aside on taking his position as CSA at DECC

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Dr Nick Hughes, Interim Policy Advisor, Royal Academy of Engineering

Notes

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