Centre for Low Carbon Futures 2050

Pathways for energy storage in the UK

AUTHORS

Peter Taylor
University of Leeds

Ronan Bolton
University of Leeds

Dave Stone
University of Sheffield

Xiao-Ping Zhang
University of Birmingham

Chris Martin
University of Leeds

Paul Upham
University of Leeds
Finnish Environment Institute

CO-AUTHORS

Yongliang Li
University of Leeds

Richard Porter
University of Leeds

Eduardo Pereira Bonvallet
University of Birmingham

Publication date

27 March 2012

Report no.

007

Publisher

The Centre for Low Carbon Futures 2012
For citation and reprints, please contact the Centre for Low Carbon Futures.

The report takes an integrated approach to examining the drivers and barriers to the development and deployment of different forms of energy storage in the UK. It uses a number of scenarios for the development of the UK energy system to analyse the different technologies and markets for energy storage and the likely timeframe for market development.

UNIVERSITY OF LEEDS The University Of Sheffield. UNIVERSITY OF BIRMINGHAM

CONTENTS

Report no: 007

Publication date: 27 March 2012

FOREWORD

The UK has significant technology and policy gaps that need closing if it is to deliver on the legislated 80% carbon reduction by 2050. The lack of suitable planned energy storage capability is at the top of this list. The ability to store energy is a key component to ensure national security of energy supply and allow credible implementation of renewable energy and to use available sources of heat.

Unlike coal, gas and petroleum, which are available in a physical form, renewable supplies of energy (solar, wind, wave) are 'virtual' and often only available at a specific location and moment in time. Renewable energy forms need to be captured and stored to supply increasingly complex user demands.

This is a core requirement for our national resilience to an increasing reliance on such variable energy sources. Recently we have become all too familiar with the dire consequences of the gap in our storage capacity – most notably through the example of wind power suppliers being paid not to generate and supply into the grid even when the wind is active!

Future scenarios indicate that energy storage is essential to reduce the burden on the national grid. The use of electric vehicles and ground source pumps in domestic use will increase demand very substantially and intolerably on our grid. Storage is not an option but a necessity.

Key challenges for the UK are to:

- understand what types of storage are needed, how much and where it should be deployed in the energy system
- develop a coherent policy approach to energy storage
- stimulate governance and business models to enable rapid implementation.

Technologically speaking, energy can be stored in mechanical, electrical or chemical devices and in the form of heat. All are probably needed, but in the UK – other than pumped hydroelectric storage – there have been few examples at a significant scale. The need for flexibility in supply means that it is likely that several different types of storage may be needed, since some can be switched on quickly (batteries) whereas others require some time before providing an energy supply (heat, hydroelectric). The place of deployment of different technologies is likely to be at city, region, home and personal/domestic device level. Very large-scale storage capacity is likely to be associated with industrial operations or at points of generation and distribution. The role of the distribution network and its flexibility is an essential component in the delivery and overall cost and viability of any storage scheme. Clearly the point of deployment affects the grid demand and methods through which it may be controlled.

In 2010, the Royal Academy of Engineering initiated a series of workshops to explore these issues in collaboration with the Chinese Academy of Sciences. The contrasting political settings, mix of energy supplies and storage technologies provided a stimulating set of comparisons between the two countries. These workshops[1] were pivotal in stimulating a range of specialised activities in system modelling, comparison of demonstrator sites and comparison of technological advances.

This report, 'Pathways for Energy Storage in the UK', is a further outcome from the workshops and aims to consider some of the key barriers and needs in a UK context. Crucially it sets the scene on a range of future developments to the energy system, in particular assumptions around enhanced use of renewables, greater use of electric and hybrid vehicles, and moves towards electrification of heat. The report details the current status of electrical energy storage devices and thermal storage devices. Scenarios for the future market and regulatory structures for energy are painted along with likely consumer reaction to the deployment of various types and scales of energy storage. The concluding discussion explores three pathways based on governance and business operations that may be described as being wholly 'user-led'; 'decentralised' and finally 'centralised'.

A core message is that energy storage encompasses a rich and varied range of technologies, involving both electricity and heat, which can be applied at the micro, meso and macro-scale and can provide benefits across the energy value chain. However, we currently have a poor understanding of these benefits, which often can be spread across different actors in the energy system. There is a risk that this lack of understanding, coupled with market and regulatory arrangements that may not always recognise the system benefits of storage, could lead to wrong solutions or sub-optimal solutions being adopted. An example of this might be over-reliance on assumed benefits from smart metering and use of so-called smart grids using a myriad of technological meters and devices under sophisticated computer control.

Alongside the conclusions, the report provides a commentary on the state of advancement internationally – similarities can be seen but in some cases storage has been aligned as part of larger scale hybrid solutions (e.g. alongside solar projects).

It is hoped this report will further stimulate detailed and more rapid considerations of options for energy storage suited for the UK needs, which can be accompanied and stimulated by policies that result in truly optimal national solutions. This review group makes specific recommendations for moving towards such an integrated energy system.

Richard A Williams OBE FREng FTSE
Royal Academy of Engineering, London

1. The Future of Energy Storage Technologies and Policy, Royal Academy of Engineering (London) and Chinese Academy of Sciences (Beijing), 2012.

PREFACE

Talk of energy storage technologies and understanding of its role can be ambiguous at best; however energy storage could end up being the hidden gem for our future management of energy. That means a huge opportunity for British research and industry at home and abroad.

There are a number of factors and events coming to a critical stage over the next couple of years making the argument for an increased focus on energy storage more compelling.

The planned decarbonisation of power generation, the electrification of heat and vehicles and our increasing dependence on renewable energy will require a careful balance of energy supply with demand to overcome issues including the intermittency of wind, solar PV and thermal power generation. The much heralded 'game changing' green policies, such as the 2012 roll out of the Green Deal by the UK Coalition Government, are planned to stimulate further implementation of energy storage dependent technologies that progress us towards 2050 carbon reduction targets. The combined impact of these policy interventions will increase current stresses on our ageing National Grid, which by 1950s design has an average capacity per household that could require a threefold increase in order to manage the increased usage of technologies, such as heat pumps and overnight charging of electric vehicles.

The questions that need to be asked are not restricted to who will pay or which technology we should deploy. Moreover it is a question of taking a whole systems approach into account for future design of an upgraded National Grid considering our planned energy mix, interconnects with European neighbours and the deployment of energy technologies for appropriate demand response times and locations. Simply put, the huge investment made in renewable wind energy and the surrounding public controversy will have little value until we can resolve some of these energy storage questions. However, energy storage to date has been under-represented in government scenarios on decarbonisation. This report shows how crucial it will be in our effective management of energy and highlights emerging evidence that decentralised storage options, on the distribution network or in people's homes, could offer most value to the energy system.

The good news is that in the UK we have a wealth of home grown technology opportunities as valuable to us as they are to emerging economies, providing an exciting and new opportunity for UK research and industry.

Stimulated by a series of joint British Sino workshops on Energy Storage Technologies and Policy, led by Professor Richard Williams from the Royal Academy of Engineering and Professor Li Jinghai, VP of the Chinese Academy of Sciences, the Centre for Low Carbon Futures commissioned this research with the aim of addressing some of the issues outlined above. We are very grateful to the contributors from those dialogues that have been instrumental in the compilation of this report. This is just one of a number of pieces of research being undertaken on this important issue and we hope that it makes a significant contribution towards the development of a long-term, joined up plan for energy storage in the UK.

Jon Price, Director
The Centre for Low Carbon Futures

EXECUTIVE SUMMARY

The United Kingdom has made a commitment to reduce greenhouse gas emissions by at least 80% below base year levels by 2050. A system of carbon budgets have been introduced which provide legally binding limits on the amount of emissions that may be produced in successive five-year periods, beginning in 2008. The fourth carbon budget, covering the period 2023–27, was set in law in June 2011 and requires emissions to be reduced by 50% below 1990 levels.

Meeting these greenhouse reduction targets will require significant changes to the way that energy is produced and used. These changes will include a huge increase in the use of renewable energy, a substantial increase in the use of electricity to provide heat and transport and sustained improvements in energy efficiency.

These developments are likely to pose significant challenges for the energy system in matching supply and demand, and so create opportunities for the deployment of additional electricity and heat storage. The opportunities will exist across a range of applications and scales – from macro, centralised storage to micro and meso-scale decentralised storage – and for storage durations from seconds through to months.

However, storage is not the only solution to meeting these challenges. Back-up fossil generation capacity, interconnectors and flexible demand, amongst others, can also play a role. The most appropriate contribution from energy storage is currently poorly understood and will be impacted by a wide range of technical, economic, market, regulatory and social factors.

This report uses an integrated systems approach to assess the role of energy storage, taking into account the range of factors that can impact its deployment. It finds that, despite being under-represented in many existing scenarios on decarbonisation, energy storage could be crucial in helping achieve a cost effective, low carbon energy system – by improving the utilisation of generation assets, avoiding investment required in transmission and distribution networks and reducing investment in back up generation. There is also emerging evidence that decentralised storage options, including heat storage located on the distribution network or in people's homes, could offer most value to the energy system.

The report identifies many different technologies for heat or electrical storage at different stages of maturity and with a wide range of characteristics. It is unlikely that a single solution will emerge in the future given the wide variations in possible applications. Further research is therefore needed into both technologies that can offer long-term large scale storage solutions and those that can provide fast response. Decentralised electrical and heat storage technologies are also worth investigating further. Energy storage also currently faces a number of regulatory and market barriers. While energy storage can provide significant system benefits, it is often too expensive for any discrete part of the value chain to realise a sufficient return on investment. New regulatory and business models will therefore be needed to exploit its potential. Public attitudes towards energy storage could be crucial in determining its role in the energy system, but to date little or no work has been undertaken in this area. Empirical studies are needed to understand the ways in which customers engage with different energy storage technologies and how this might influence their uptake.

Given these findings, there is an urgent need for a long-term vision for storage that is consistent with developments in the wider energy system. This might best be achieved through a UK roadmap for energy storage that brings together relevant stakeholders, including government, researchers, business, regulators and representatives from civil society.

1: INTRODUCTION

The UK has ambitious goals for greenhouse gas reduction over the period to 2050 that will require the rapid decarbonisation of its energy system. Until recently, little attention had been given to the role of energy storage in helping to achieve these goals.

However, in summer 2011, the Energy Research Partnership (ERP) released a report highlighting that energy storage could have an important role to play in helping to facilitate a low-carbon energy transition, but that it currently faces a number of technical and market/regulatory challenges (ERP, 2011). Participants at a UK Energy Research Centre workshop held earlier in 2011 concluded that examining the potential of energy storage should involve a 'holistic approach', requiring "system-wide studies" and "joined-up thinking" that recognise both the "interdisciplinary nature of many of the issues relating to storage and how these can be considered sufficiently comprehensively" (UKERC, 2011). The Royal Academy of Engineering and the Chinese Academy of Sciences also held workshops on energy storage during 2011 to highlight key strategic needs for research and identify areas for bilateral co-operation.

The purpose of this report is to examine key drivers and barriers to the development and deployment of electricity and heat energy storage in the UK and to identify further work necessary to understand and facilitate its appropriate role within a low-carbon energy system. It does this by bringing a whole systems understanding of the factors that impact energy storage and integrating these different perspectives in a number of pathways for storage to identify the likely timeframe over which the market could develop.

STORAGE IN THE CURRENT UK ENERGY SYSTEM

When the term 'energy storage' is used, most people think about the storage of electricity or perhaps heat and, indeed, storage of energy in these themes is the main focus of this report. However, it is important to remember that most of the energy storage capacity in the current UK energy system is provided by stocks of fossil fuels. One estimate puts the electricity that could be generated from UK stocks of coal and gas destined for the power sector at around 30 000 GWh and 7 000 GWh respectively (Wilson, 2010).

These fossil fuel stocks are far greater than the storage available within the electricity system itself. Bulk storage of electricity is currently largely provided by pumped hydroelectric plants connected to the transmission system. There are four major schemes in the UK, all now more than 30 years old, with an installed capacity of 2.7 GW and a volume of 27.6 GWh. There are also a few smaller electricity storage facilities (mostly demonstration projects involving different types of battery) connected to the distribution system in various parts of the country.

Heat storage is largely distributed and mostly at an individual building scale. Almost 14m households in the UK have a hot water cylinder (CLG, 2009), giving a maximum combined storage capacity of around 80 GWh[2]. However, the volume of this kind of hot water storage is on the decline as 80% of sales of new gas boilers are of the combi variety that do not require a hot water tank (Royal Academy of Engineering, 2012). A number of district heating schemes in the UK also have hot water storage associated with them. One of the largest is in Pimlico in London, consisting of a 3.4 MW_{th} combined heat and power (CHP) plant and an accumulator that can store 2,500m^3 of water at just less than boiling point. The other major form of heat storage is electrical storage heaters. These use off-peak electricity to store heat (in high density bricks), which is released throughout the course of the day. Around 1.6m dwellings in the UK (mostly flats) have storage heaters as their primary heating system (BRE, 2007).

FUTURE MARKETS FOR ELECTRICITY AND HEAT STORAGE

Electricity and heat storage can play an enabling role in any energy system, facilitating the matching of supply and demand at intervals from seconds through minutes, hours and days by their ability to 'time-shift' both supply and demand. One of the major benefits of storage is that it can improve the utilisation of other energy assets, so potentially enhancing the overall technical and economic efficiency of the system (if the overall system efficiency gain is greater than the efficiency loss in the storage itself).

In the future there are likely to be a number of developments that could pose challenges for the energy system in matching supply and demand and so create opportunities for the deployment of additional electricity and heat storage. These opportunities will potentially exist across a range of applications and scales from macro, centralised storage to micro and meso-scale decentralised storage and for storage durations from seconds through to months. Some of the most important challenges and possible storage solutions are summarised in Table 1.1. However, storage is not the only solution to meeting these challenges. Back-up fossil generation capacity, interconnectors and flexible demand, amongst others, can also play a role.

2. Assuming an average sized tank is 100 litres and holds water heated to 50°C.

TIMESCALE	CHALLENGE	POTENTIAL STORAGE SOLUTION
SECONDS	Some renewable generation introduces harmonics and affects power supply quality.	Very fast response/low volume electricity storage associated with generation, transmission or distribution.
MINUTES	Rapid ramping in response to changing supply from wind generation affecting power frequency characteristics.	Relatively fast response electricity storage associated with generation, transmission or distribution.
HOURS	Daily peak for electricity is greater to meet demand for heat and/or recharging of electric vehicles.	High-power bulk electricity storage to meet peaks in electricity. Distributed electrical battery storage to smooth out charging peaks. Household level heat storage in tanks or integrated into the building fabric.
HOURS – DAYS	Variability of wind generation needs back-up supply or demand response.	Large-scale or decentralised electricity storage to back-up wind generation.
	Increased use of electricity for heat causes increased variability in daily and weekly demand.	Heat storage at community or building level, use of CHP with storage to act as a buffer between electricity and heat.
MONTHS	Increased use of electricity for heat leads to strong seasonal demand profile.	Large scale inter-seasonal heat storage associated with combined heat and power and district heating schemes or use of novel materials to provide longer duration heat storage in buildings.

Table 1.1 Future challenges to the UK energy system that could be addressed by energy storage.
Source: Adapted from ERP (2011)

FACTORS IMPACTING THE FUTURE DEVELOPMENT OF ELECTRICITY AND HEAT STORAGE

The extent to which the market for electricity and heat storage will develop in the UK is dependent on a wide range of technical, economic, regulatory and social factors (Figure 1.1).

Some of the most important include:

- the wider development of the UK energy system, which may provide opportunities for the services that storage provides, but may also encourage competing solutions;
- research and development into electricity and heat and storage technologies, which may result in more or less favourable trends in the cost and performance of existing storage options, as well as providing new alternatives;
- developments in the structure of heat and electricity markets in the UK, which may encourage storage as a solution or present barriers;
- developments in the organisational structures of actors in the electricity markets that may encourage or hinder new business models promoting energy storage;
- public attitudes and behaviours, which may find different scales and technologies for storage more or less acceptable and more or less easy to integrate into lifestyles.

THE FOLLOWING SECTIONS IN THE REPORT CONSIDER THESE ISSUES IN MORE DETAIL, BEFORE INTEGRATING THEIR FINDINGS IN A RANGE OF POSSIBLE PATHWAYS FOR THE DEPLOYMENT OF ENERGY STORAGE IN THE UK.

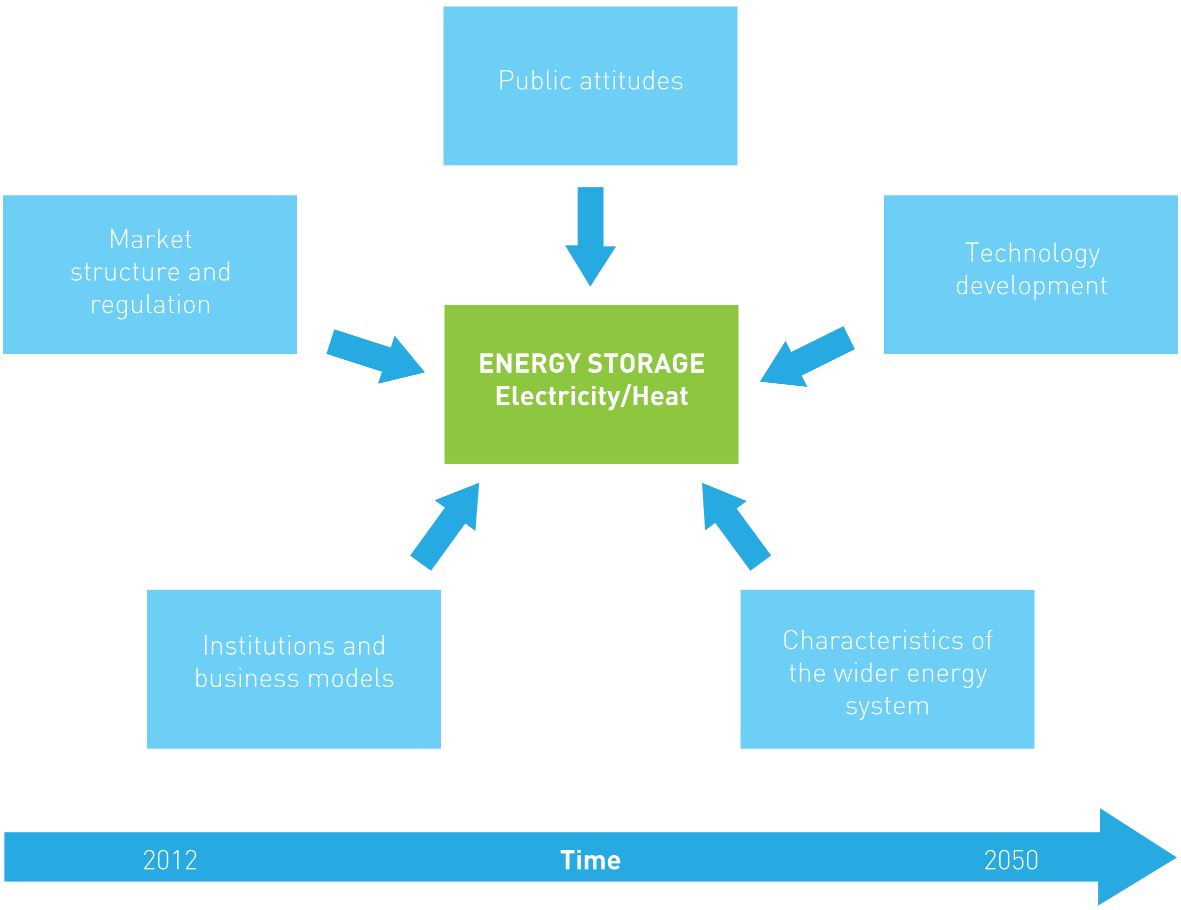


Figure 1.1 Factors impacting the deployment of energy storage in the UK.

2: FUTURE DEVELOPMENTS IN THE UK ENERGY SYSTEM

The Climate Change Act established a legally binding target to reduce the UK's greenhouse gas emissions by at least 80% below base year levels by 2050 (Great Britain, Climate Change Act 2008)[3].

To achieve sustained emissions reductions towards this target, the Act introduced a system of carbon budgets which provide legally binding limits on the amount of emissions that may be produced in successive five-year periods, beginning in 2008. The fourth carbon budget, covering the period 2023–27, was set in law in June 2011 and requires emissions to be reduced by 50% below 1990 levels.

Meeting these targets will require massive changes in the way that the UK supplies and uses energy. Scenarios produced by the Government in its Carbon Plan (Box 2.1) show that the share of fossil fuel use in the primary fuel mix will fall from around 90% today to between 13% and 43% by 2050. In contrast, the share of renewable energy will increase to between 36% and 46% from a level of less than 4% today. Even by 2030 the energy mix could look quite different, with fossil fuels accounting for less than two-thirds of the primary fuel mix and renewables for more than a quarter. A second major trend is the greater use of electricity – particularly to provide heat and transport. The proportion of electricity in total final demand is currently around 18%, but under the Carbon Plan scenarios this share increases to between 25% and 31% by 2030 and between 33% and 44% by 2050. All scenarios also show a substantial increase in energy efficiency.

Much of the storage capability of the energy system is currently provided by fossil fuels. However, with the share of these declining and a much greater use of renewable energy as a primary energy carrier and electricity as a secondary carrier, there is likely to be a greater emphasis on the potential for directly storing electricity and heat. The precise role that energy storage will play will be impacted by developments right across the energy system. Some of the most important are discussed below.

INCREASE IN VARIABLE RENEWABLE ELECTRICITY GENERATION

The share of electricity generation from variable renewables (taken in this report to include onshore and offshore wind, photovoltaics and tidal and wave power) increases rapidly from less than 5% today to between 15% and 26% by 2020 depending on the scenario (Figure 2.2). All Carbon Plan scenarios then show the share of variable renewables peaking between the years 2030 and 2040 at between 19% and 64%. This corresponds to an installed capacity of 28 GW to 91 GW.

After 2030, the absolute amount of electricity generation from variable renewables stabilises or falls slightly in all scenarios except the high renewables variant, as the role of nuclear and thermal plant with carbon capture and storage (CCS) becomes more important. By 2050 the variable renewable shares are therefore somewhat lower than their peak values at between 11% and 61% (corresponding to an installed capacity of 20 GW to 106 GW). This potentially implies a significant increase in the need for additional reserve and response capacity over the period from 2020 to 2030, in addition to the extra 3 GW that already have been identified by National Grid for the period to 2020 (National Grid, 2011a).

3. Greenhouse gas emissions reduction achieved outside the UK can count towards the target.

AS PART OF ITS CARBON PLAN (DECC 2011A), THE GOVERNMENT PRESENTS FOUR ALTERNATIVE SCENARIOS TO 2050 IN ORDER TO UNDERSTAND THE POTENTIAL ROLE OF DIFFERENT SUPPLY AND END-USE TECHNOLOGIES OVER THE NEXT 40 YEARS.

THERE ARE MANY THOUSANDS OF PLAUSIBLE PATHWAY COMBINATIONS WHICH COULD BE POSSIBLE AND THE GOVERNMENT NOTES THAT THE ELECTRICITY GENERATION MIXES, DEGREE OF ELECTRIFICATION AND LEVELS OF DEMAND REDUCTION SHOWN IN THESE FUTURES SHOULD NOT BE SEEN AS THE ONLY LIKELY OR AVAILABLE COMBINATIONS.

HOWEVER, THE SCENARIOS PROVIDE A USEFUL INDICATION OF THE SCALE, PACE AND DIRECTION OF CHANGE TO THE UK ENERGY SYSTEM OVER THE NEXT 40 YEARS.

The starting point for the scenarios is the outputs from the 'core' run of the cost-optimising model, MARKAL, which was produced as part of the Department of Energy and Climate Change's analysis to support the setting of the fourth carbon budget. Alongside this, the Government has developed three further 'futures' that attempt to stress test the results of the core run by recognising that it is not possible to predict accurately trends in the development, cost and public acceptability of different technologies in every sector of the economy.

Future 'Higher renewables, more energy efficiency' assumes a major reduction in the cost of renewable generation alongside innovations that facilitate a large expansion in electricity storage capacity. It is consistent with a world where high fossil fuel prices or global political commitment to tackling climate change drives major investment and innovation in renewables.

Future 'Higher CCS, more bioenergy' assumes the successful deployment of CCS technology at commercial scale and its use in power generation and industry, supported by significant natural gas imports, driven by changes such as a reduction in fossil fuel prices as a result of large-scale exploitation of shale gas reserves. It also assumes low and plentiful sustainable bioenergy resources.

Future 'Higher nuclear, less energy efficiency' is a future that is more cautious about innovation in newer technologies. CCS does not become commercially viable. Innovation in offshore wind and solar does not produce major cost reductions. Lack of innovation in solid wall insulation results in low public acceptability of energy efficiency measures.

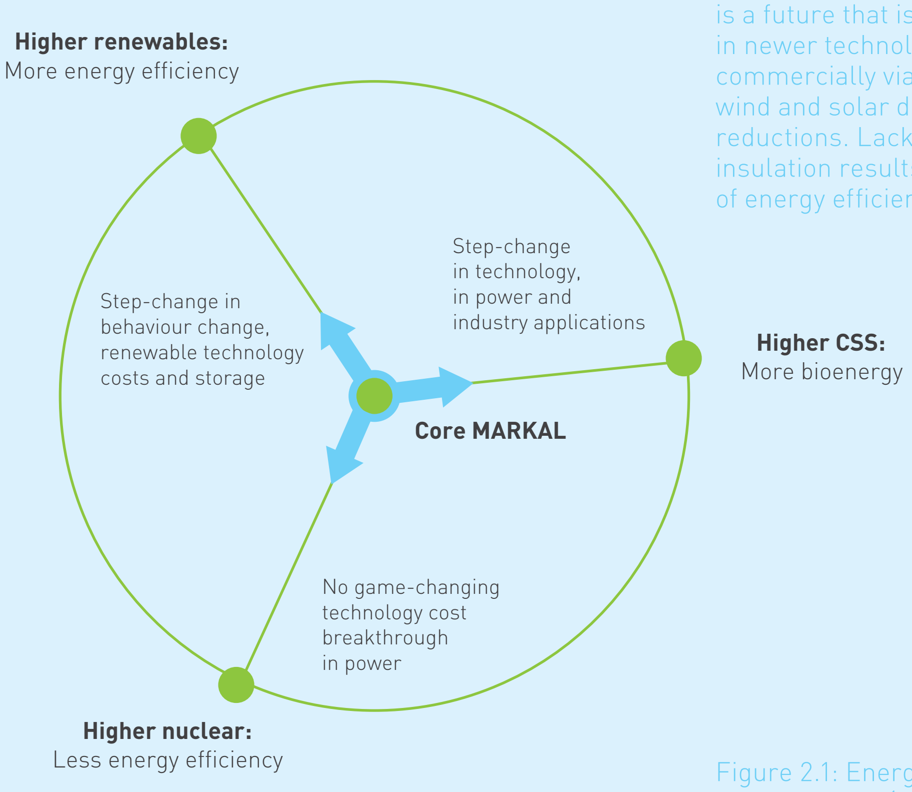


Figure 2.1: Energy Futures to 2050.
Source: DECC (2011a)

Box 2.1: Long-term scenarios in the UK Carbon Plan.

Figure 2.2: Share of electricity generation from variable renewables.

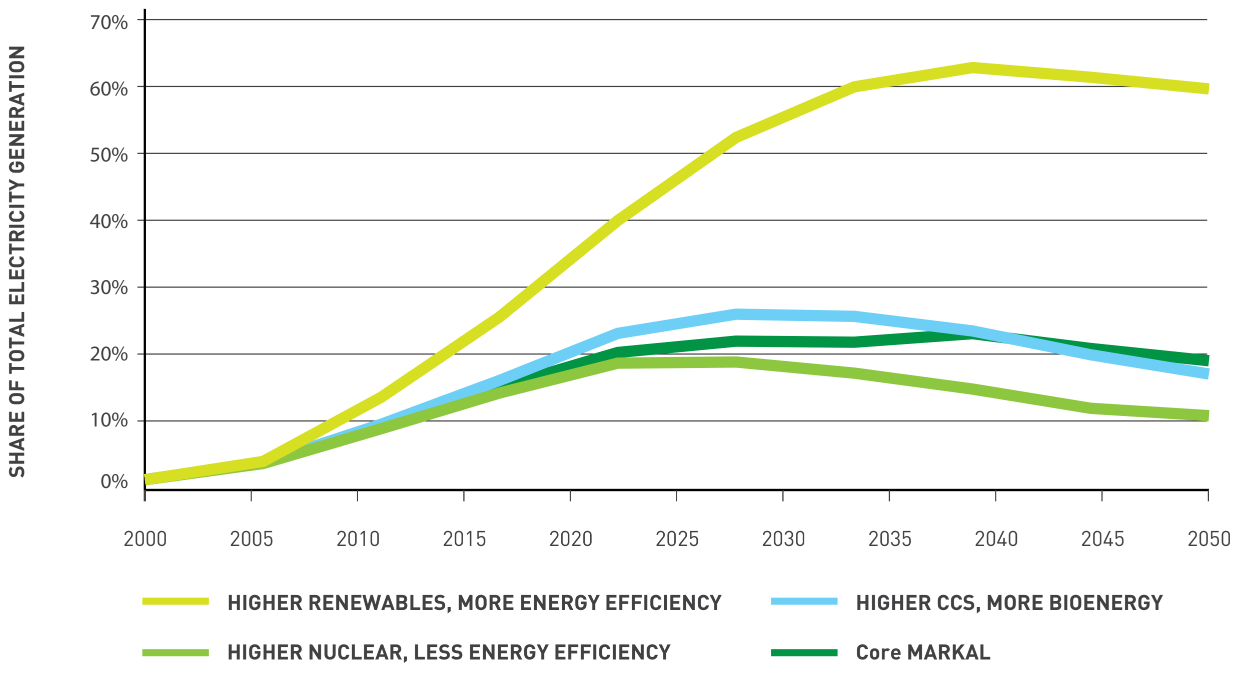


Figure 2.3: Share of households using electricity as their main heating source.

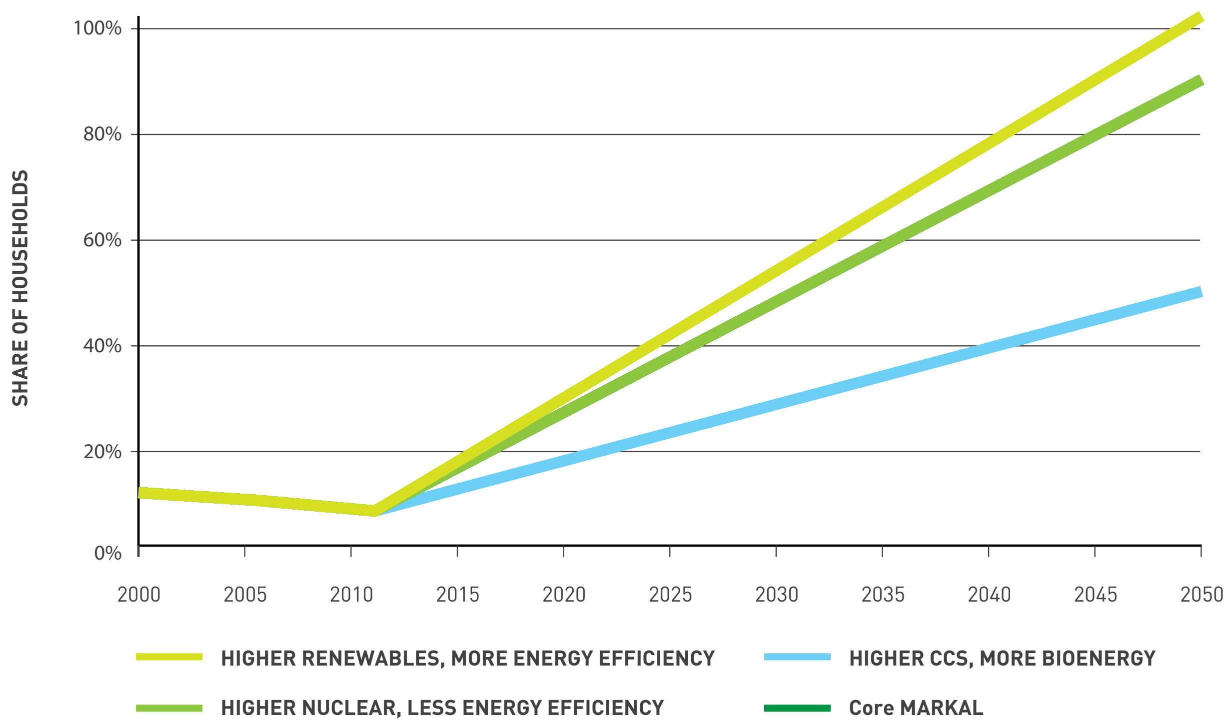


Figure 2.4: Share of PHEVs in meeting passenger car demand.

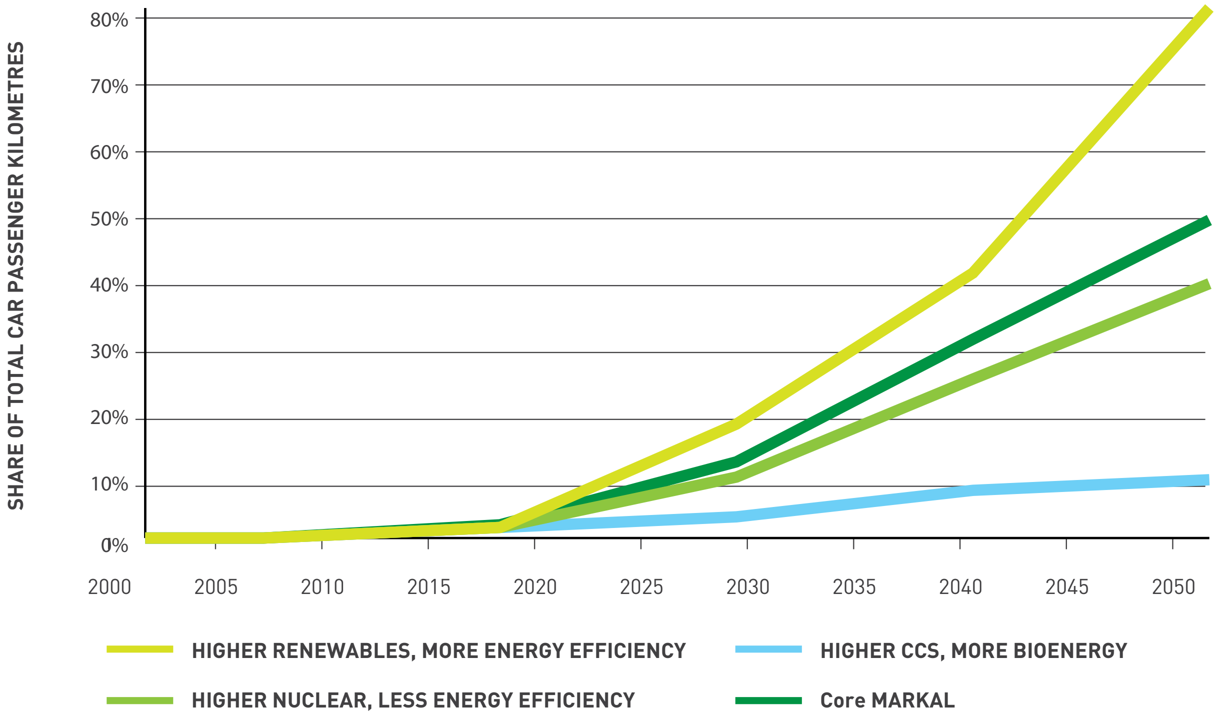
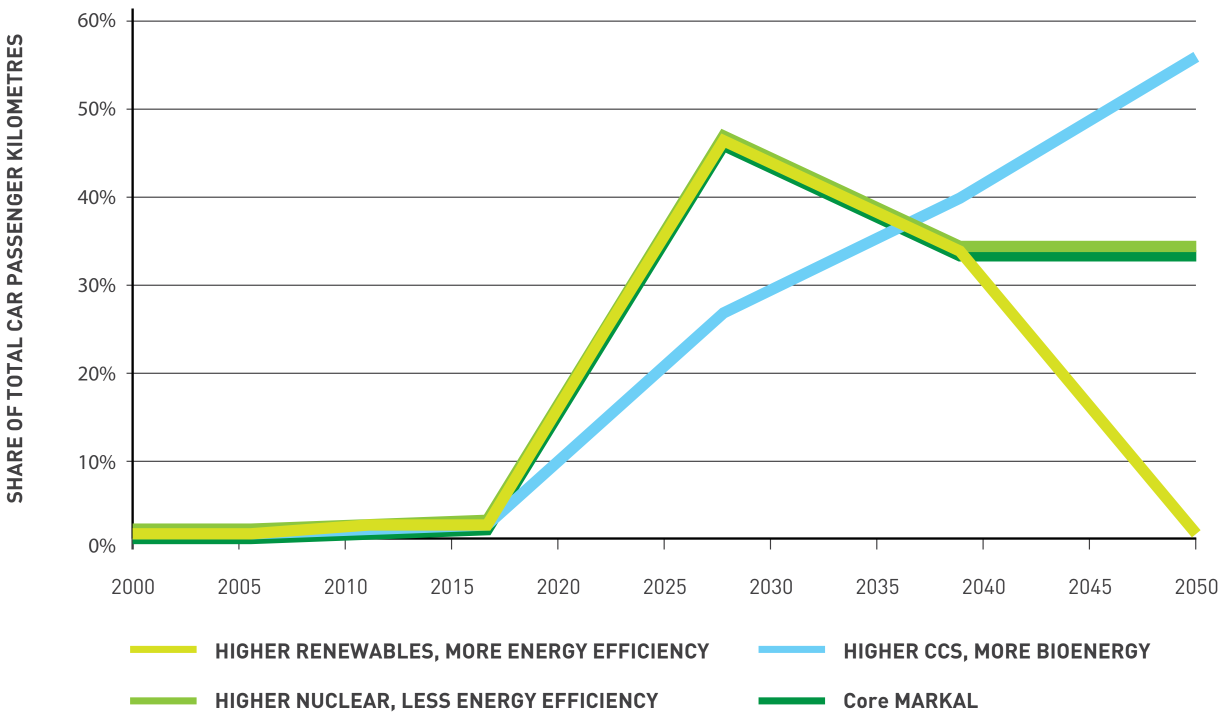


Figure 2.5: Share of EVs in meeting passenger car demand.



Source: based on data from the DECC Excel 2050 Calculator (www.decc.gov.uk/en/content/cms/tackling/2050/2050.aspx)

ELECTRIFICATION OF HEAT

The trends in the electrification of household heating show a small decline to 2015, as existing electrical heating systems are retired, followed by a sustained increase in all scenarios driven by the deployment of both air and ground source heat pumps. By 2020, the share of households with electric heating ranges between 13% and 20% and this proportion grows steadily over the next 30 years under all scenarios. By 2030, between 18% and 33% of households have electric heating and this grows to between 48% and 100% by 2050, depending on the scenario.

The implications for this trend in terms of peak electricity demand could be very significant. As an illustration, if 10 million homes (around 40% of the total) replaced their gas boilers with air source heat pumps, each with a 5 kW_e peak load, this would have the potential to create up to 50 GW of additional electricity demand (Speirs, 2010). Furthermore, the peaks in heating demand could coincide with the existing morning and evening peaks in electricity demand. Combining heat pumps with thermal storage could facilitate a different mode of operation, enabling significant use of off-peak electricity.

Analysis for the Climate Change Committee suggested that a 2,500 litre hot water accumulator coupled with a 9 kW_{th} heat pump would allow between 70% to 90% of heat demand to be during off-peak hours on an Economy 10 tariff (NERA and AEA Technology, 2010). However, the Royal Academy of Engineering have noted that well insulated hot water tanks or underground inter-seasonal thermal stores will be simpler to provide on a community basis given the small (and reducing) size of most UK homes (Royal Academy of Engineering, 2012).

DEPLOYMENT OF PLUG-IN HYBRID AND ELECTRIC VEHICLES

Another important future demand for electricity is likely to come from the deployment of plug-in hybrid vehicles (PHEV) and all-electric vehicles (EVs). All the scenarios show that, in the period to 2040, it is likely PHEVs will be the most important battery vehicle technology. In 2025 PHEVs account for 13% to 23% of all passenger-kilometres travelled by car, rising to between 32% and 38% by 2040.

After 2040, the share of PHEVs stabilises or starts to decline in all scenarios except the CCS variant. In contrast, the share of EVs increases significantly from 2020 onwards in all scenarios except the CCS variant, meeting between 38% and 80% of total passenger car demand in 2050 across the other three scenarios. Thus, across all four scenarios, the combined share of EVs and PHEVs increases from between 15% to 32% in 2025 to between 63% and 80% in 2050. Again the impact on electricity demand could be significant. For instance, if the entire population of light/medium size vehicles was converted to electricity, the total daily energy requirement would amount to around 150 GWh (Strbac, 2010).

The possible impacts of PHEVs and EVs on the market for energy storage are complex. On the one hand, greater electrical energy storage may be needed at a household level to buffer the demand from recharging vehicles. For example, a battery unit located in the garage could be trickle-charged using off-peak electricity and then used to provide more rapid charging as needed to the vehicle. On the other hand, PHEVs and EVs could themselves be used as a source of electrical storage through the use of 'smart' charging and vehicle-to-grid (V2G) technology.

OTHER CHANGES

Other potential changes to the UK energy system could positively or negatively impact on the amount and type of storage required. These include:

Cost and degree of flexibility of fossil-fuelled back-up generation. Currently most large-scale reserve and response functions on the electricity grid are provided by flexible fossil fuel generation, including open cycle gas turbines, combined cycle gas turbines and steam-cycle coal plant. All the Carbon Plan scenarios show that the amount of fossil-fuelled electricity generation will decline substantially in the future with shares of between 2% and 54% by 2050. Much of the generation that remains will be combined with CCS.

The extent to which any remaining fossil fuel plants will continue to play a role in providing reserve and response functions and so limit opportunities for storage may depend on a combination of factors. These include the flexibility of large-scale fossil fuel plants when using CCS and the economic viability and environmental acceptability (in terms of CO_2 emissions) of smaller, dedicated fossil fuel back up plants (without CCS) operating at very low load factors (dependent on both investment and operating, mostly fuel, costs).

Deployment of CHP and district heating. While most of the scenarios in UK Carbon Plan anticipate that electricity (heat pumps) will become the dominant energy source for heating in households, the CCS variant shows a substantial increase in community scale CHP. By 2030 19% of households have this as their major heating source, rising to 39% by 2050. Other studies have concluded that CHP and district heating could have an enhanced role in a decarbonised energy system (e.g. Speirs, 2010; Rhodes, 2012). While a greater penetration of CHP and district heating may lower the demand for electric heating and associated storage at the household level, it could itself be combined with larger scale hot water accumulators or other storage devices.

Uptake of space cooling. Energy demand for space cooling has been growing since the 1970s, largely as result of its use in the service and commercial sectors. It is only relatively recently that air conditioning has started to penetrate households. For domestic cooling, the Carbon Plan scenarios range in assumptions between no additional domestic air conditioning used over the period to 2050 relative to today, and two-thirds of households having air conditioning by 2050. In the case of commercial buildings, the assumptions span 40% of non-domestic floor space being air-conditioned in 2050, to achieving a 90% reduction in cooling demand compared with an average air conditioned building within the existing stock in 2007. Increased demand for cooling could create additional demands for storage that can handle both heating and cooling, such as the integration of phase change materials into the fabric of buildings.

Level of interconnection with other countries. Currently, the UK is connected to France via a 2GW DC line, the 1 GW BritNed connector to the Netherlands and a 0.5 GW link from Scotland to Ireland. There are plans to build further interconnectors with other countries including Ireland, Belgium, Norway and France (DECC, 2010). Most of the scenarios in the Carbon Plan foresee the level of interconnection increasing to 8 GW in 2025 and to 10 GW by 2050. However, for the renewables variant the capacities are 15 GW and 30 GW respectively. Interconnection could provide an alternative to storage in some cases but it could also generate additional storage demands, for instance in the case that it was economically viable to store off-peak electricity imported from continental Europe.

Degree of demand-side flexibility. The ability to flex demand (i.e. by shifting load from one time period to another) could play a major role in matching supply and demand. In the case of electricity demand, such flexibility could be facilitated by the roll-out of smart metering. For heat demand, building level storage could have an important role to play. In principle, a wide range of electrical appliances could be involved in providing flexible demand. In the Carbon Plan scenarios, the focus is on the role that PHEVs and EVs could play. This could involve short-term periods of flexibility, for example short-term variations in the pattern of demand for overnight charging as well as longer-term flexibility, facilitated by higher car battery capacity, which could involve flexibility in charging patterns over a week. In addition, PHEVs could run solely using their internal combustion engine, hence reducing electricity demand from recharging the battery.

Under the Carbon Plan scenarios, the share of all EVs that have shiftable demand capacity ranges between 25% and 75%, with figures for the share of PHEVs varying between 30% and 90%. In addition, some flexibility in space and water heating is assumed; with up to 12 hours for space heating in a well-insulated home and between 12 and 24 hours for water heating. Modelling work has indicated that optimising demand response can result in massively improved utilisation of generation and network capacity, and significantly reduced network investment, even for very low levels of penetration of electric vehicles and heat pumps (Strbac, 2010).

CONCLUSIONS

The direction of future developments in the UK energy system will have a profound impact on the markets for both electricity and heat storage. While there are many scenarios for the future, the majority show a dramatic fall in the use of fossil fuels and growing dependence on both renewable energy and the use of electricity. These trends are likely to pose additional challenges in terms of matching supply and demand for energy, since the existing fossil fuel storage capacity of the energy system will be much reduced. The role for both heat and electricity storage is therefore likely to increase.

However, the extent of the market for storage and the precise applications needed are much more uncertain. Some trends, such as an increase in the amount of generation from variable renewable energy and greater electrification of heat, are likely to increase the market for storage. Others, such as greater demand flexibility, may provide competition and squeeze storage out of certain applications. Other changes, such as the impact of EVs and greater interconnection are much more uncertain. A summary of these factors is provided in Table 2.1

DEVELOPMENT	ELECTRICAL ENERGY STORAGE	HEAT ENERGY STORAGE
MORE VARIABLE RENEWABLE ENERGY	Positive for all scales and for both power and energy storage	Could be positive if used with combined heat and power as a buffer between electricity and heat
ELECTRIFICATION OF HEAT	Could be positive – particularly at macro and meso-scale (system operator and distribution network operators managing demand)	Positive at micro-scale (combined with heat pumps), but less so at meso-scale (less market for DH)
PHEVS AND EVS	Uncertain – could provide additional opportunities or compete for some services	Little impact
LOW COST AND FLEXIBLE FOSSIL FUEL GENERATION	Negative for macro-level reserve and response functions	Negative for macro-scale inter-seasonal storage
INCREASED CHP AND DISTRICT HEATING	Negative for meso and micro-scale storage	Positive for macro and meso-scale storage, but negative for micro-storage at household level (unless combined with micro-CHP)
INCREASED DEMAND FOR SPACE COOLING	Positive if can help smooth demand	Positive for systems that combine heating and cooling
GREATER INTERCONNECTION	Uncertain – depending on relative electricity prices	Little impact
INCREASED DEMAND-SIDE FLEXIBILITY	Generally negative – although opportunities to contribute to increased flexibility at household level	May contribute to increased flexibility

Table 2.1: The impacts of selected energy system developments on the market for energy storage.

3: TECHNOLOGIES FOR STORING ELECTRICITY AND HEAT

There are many different technologies that can provide heat or electrical storage. Each technology has its own particular characteristics and likely market application. The technologies are currently at different stages of maturity but, in many cases, future developments in both cost and performance will be vital in determining whether they are taken up by the market. This section briefly reviews some of the most promising electricity and heat storage technologies for a wide range of applications and identifies key research and development needs.

ELECTRICAL ENERGY STORAGE TECHNOLOGIES

There are a wide range of different technologies[4] that can be used for electrical energy storage (EES), which can be grouped according to the physical or chemical principle employed:

MECHANICAL: PUMPED HYDROELECTRIC STORAGE (PHS), COMPRESSED AIR ENERGY STORAGE (CAES), FLYWHEEL;

ELECTROCHEMICAL: BATTERIES (INCLUDING NICKEL, LITHIUM-ION, LEAD-ACID, METAL-AIR AND SODIUM-SULPHUR CHEMISTRIES), FLOW BATTERIES, FUEL CELLS;

ELECTRICAL: SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES), ELECTRIC-DOUBLE LAYER CAPACITORS (SUPERCAPACITORS); AND

THERMAL: CRYOGENIC ENERGY STORAGE (CES).

PHS is the most established form of large-scale energy storage, accounting for over 99% of global EES capacity. Water is pumped from a lower reservoir to a higher reservoir when there is a surplus of electricity. This can then be released through a turbine to generate electricity at times of peak demand.

CAES is the only other commercially available technology for providing large EES. It works by using electricity to compress air and store it in large caverns. At a later time, the air is then expanded through a conventional gas turbine unit connected to a generator to produce electricity. Only two schemes have been commissioned to date, in Germany and the US.

There are a number of different types of **battery** system being considered for energy storage, including lead-acid, sodium-sulphur, lithium-ion, nickel-based and metal-air designs. Lead-acid batteries are the most mature rechargeable battery, and are low-cost and rugged. However, they tend to have limited cycle life and so are not ideal for energy management. Sodium-sulphur battery systems are commercially available, with a number of systems in Japan, the US and Europe, including a 1 MW system on Shetland. However, there have been some concerns expressed over safety following a fire in Japan in October 2011. Lithium-ion batteries are widely used in portable electronic equipment and there are a number of large-scale demonstration projects aimed at utility frequency regulation and fast response applications, including at Hemsby in Norfolk.

4. Further details and full references for each of the technologies can be found in the technology factsheets available at: www.lowcarbonfutures.org/projects/energy-systems/energy-storage

Currently, Li-ion batteries are high cost and there are a number of emerging challenges that will need to be addressed for the technology to be fully commercialised at large-scale. Nickel-cadmium batteries are the only other type of battery to be widely demonstrated at utility-scale, but cost is a significant issue. Other nickel chemistries have not yet reached large-scale implementation, although there is interest in nickel metal hydride systems. Metal-air batteries have the potential to attain very high specific energy densities, but so far are at the research and early demonstration phase.

Flow batteries operate differently from battery systems – the chemical reaction takes place in a reaction chamber, with the electrolytes stored in external tanks. Unlike a battery system, energy and power in a flow cell are independent of each other, so it is easier to develop modular systems that can be expanded as required. There are currently a number of electro-chemistries at different stages of development and deployment including the use of vanadium and zinc bromine.

CES is a newly developed EES technology. Off-peak electricity is used to liquefy air or nitrogen, which is then stored in cryogenic tanks. Ambient or other heat can then be used to superheat the cryogen, boiling the liquid and forming a high pressure gas to drive a turbine to produce electricity. CES is at an early stage of commercialisation, with a 500 kW project in the UK.

Flywheel systems consist of a motor/generator attached to a rotor of large mass. When electrical energy is to be stored the motor accelerates the flywheel and the energy is then recovered by switching the operating mode so that the flywheel drives the generator. The use of flywheel energy storage systems on a grid scale are a recent development, with a number of demonstration projects around the world. Their main advantage is the very fast response times, making them suitable for voltage and frequency stabilisation, while they possess relatively low energy capacities.

SMES stores energy in a superconducting coil in the form of a magnetic field. SMES have fast response, but can only store energy for a few hours. It is therefore most suited for grid stabilisation applications. Micro-SMES devices (smaller than 30 MW) are commercially available and there are a number of larger SMES demonstration projects around the world.

Supercapacitors consist of two metal electrodes coated with a high surface area type of activated carbon and separated by a thin porous insulator. They can store or deliver energy at a very high rate but have limited capacity compared to batteries. Traditionally they have been used to complement battery storage systems, to increase the overall power density. Standalone supercapacitor systems are still at an early demonstration phase.

Hydrogen storage and **fuel cells** are promising technologies and the subject of significant research effort. The system differs from a normal EES technology since it uses two different processes for the cycle of energy storage, production and use. An electrolyser unit separates water into oxygen and hydrogen using electricity. The hydrogen is then stored in high pressure tanks, or other forms of storage. Electricity is then produced from the stored hydrogen using an electrochemical device called a fuel cell.

Suitability of EES technologies for different applications

An ideal EES would be cheap, have high cycle efficiency, high energy and power density and a long lifetime, while being environmentally benign. A combination of these six attributes does not yet exist in a single solution, but instead different EES systems are more or less suited to different application ranges. Historically, most EES systems have been targeted towards bulk/centralised storage and have been used to provide storage over relatively long durations (such as PHS) or have been used for fast response (e.g. flywheels). However, there is an increasingly strong argument for the use of decentralised, or distributed, storage that is embedded within the distribution network, or forms an integral part of a building's electrical system. An example of this would be the deployment of small battery packs in houses alongside roof mounted solar panel installations.

TECHNOLOGY	TYPICAL RATED CAPACITY (MW)	NOMINAL DURATION	CYCLE EFFICIENCY (%)	ENERGY COST ($/ KWH)	POWER CAPACITY COST ($/ KW)	TYPICAL LIFE (YEARS)	TECHNOLOGY MATURITY	USUAL/ ANTICIPATED SCALE
PUMPED HYDROELECTRIC STORAGE	100-5000	1-24+ hrs	70-87	5-100	600-2000	30-60	Mature & Commercial	Large grid
COMPRESSED AIR ENERGY STORAGE	50-300	1-24+ hrs	70-89	2-120	400-1150	20-40	Commercial	Large grid
CRYOGEN-BASED ENERGY STORAGE	10-200	1-12+ hrs	40-90+	260-530	900-2000	20-40+	Early commercial	Grid/EV/ Commercial UPS
FLYWHEEL	0.4-20	1 - 15 mins	80-95	1000-14000	250-25000	15-20	Demo/ Early commercial	Small grid/House/EV
HYDROGEN STORAGE AND FUEL CELL	0-50	Seconds-24+ hrs	20-85	6-725	1500-10000+	5-20	Demo	Grid/House/EV/ Commercial UPS
BATTERIES: Flow	0.03-3	Seconds - 10h	65-85	150-1000	600-2500	5-30+ (200-12000 cycles)	Research/ Early demo	Grid/House/EV/ Commercial UPS
BATTERIES: Lithium	1-100	0.15-1 hrs	75-90	600-3800	400-1600	5-15 (4000-100,000 cycles)	Demo	Grid/House/EV/ Commercial UPS
BATTERIES: Metal-Air	0.01-50	Seconds-5 hrs	~75	10-340	100-1700	(100-10000 cycles)	Research/ Early demo	Grid/House/EV/ Commercial UPS
BATTERIES: Sodium-Sulphur	0.05-34	Seconds-8hrs	75-90	300-500	350-3000	5-15 (2500-4500 cycles)	Commercial	Grid/House/EV/ Commercial UPS
BATTERIES: Nickel	0-40	Seconds-hrs	60-90	800-1500	400-2400	10-20 (1500-3000 cycles)	Early commercial	Grid/House/EV/ Commercial UPS
BATTERIES: Lead-Acid	0-40	Seconds-10hrs	63-90	200-400	50-600	5-20 (200-1000 cycles)	Mature & Commercial	Grid/House/EV/ Commercial UPS
SUPERCONDUCTING MAGNETIC ENERGY STORAGE	0.1-10	Milliseconds-seconds	90-97+	1000-10000	200-350	20-30	Early commercial	Small grid/ Commercial UPS
SUPERCAPACITOR	0-10	Milliseconds -1 hr	<75-98	300-20000	25-510	8-20+ (25000-1 million cycles)	Early demo	Small grid/ House/EV

Table 3.1: A comparison of different EES technologies.

Table 3.1 summarises the cost and performance of a range of EES technologies and Figure 3.1 maps some of the most important technologies against grid-scale applications. EES technologies with a very large energy storage capacity, such as PHS and CAES, can provide enough capacity to smooth diurnal fluctuations in supply, such as storing excess electricity from a wind farm or increasing the output time of a solar array beyond daylight hours. However, these are presently the only mature solutions to such large-scale, long duration applications and, as they are both heavily dependent upon limited geographical locations, their monetary cost cannot be directly compared with solutions which benefit from portability, scalability and versatility of deployment. In the future, it is possible that redox flow batteries and hydrogen storage systems could become commercial for similar applications.

At the other end of the scale, flywheels and super-capacitors can smooth short-term fluctuations such as those caused by line faults, surges or time-varying power output from a wind-farm, while reducing the need for spinning-reserve.[5] In the future, SMES may be able to play a similar role but is currently too expensive for widespread application.

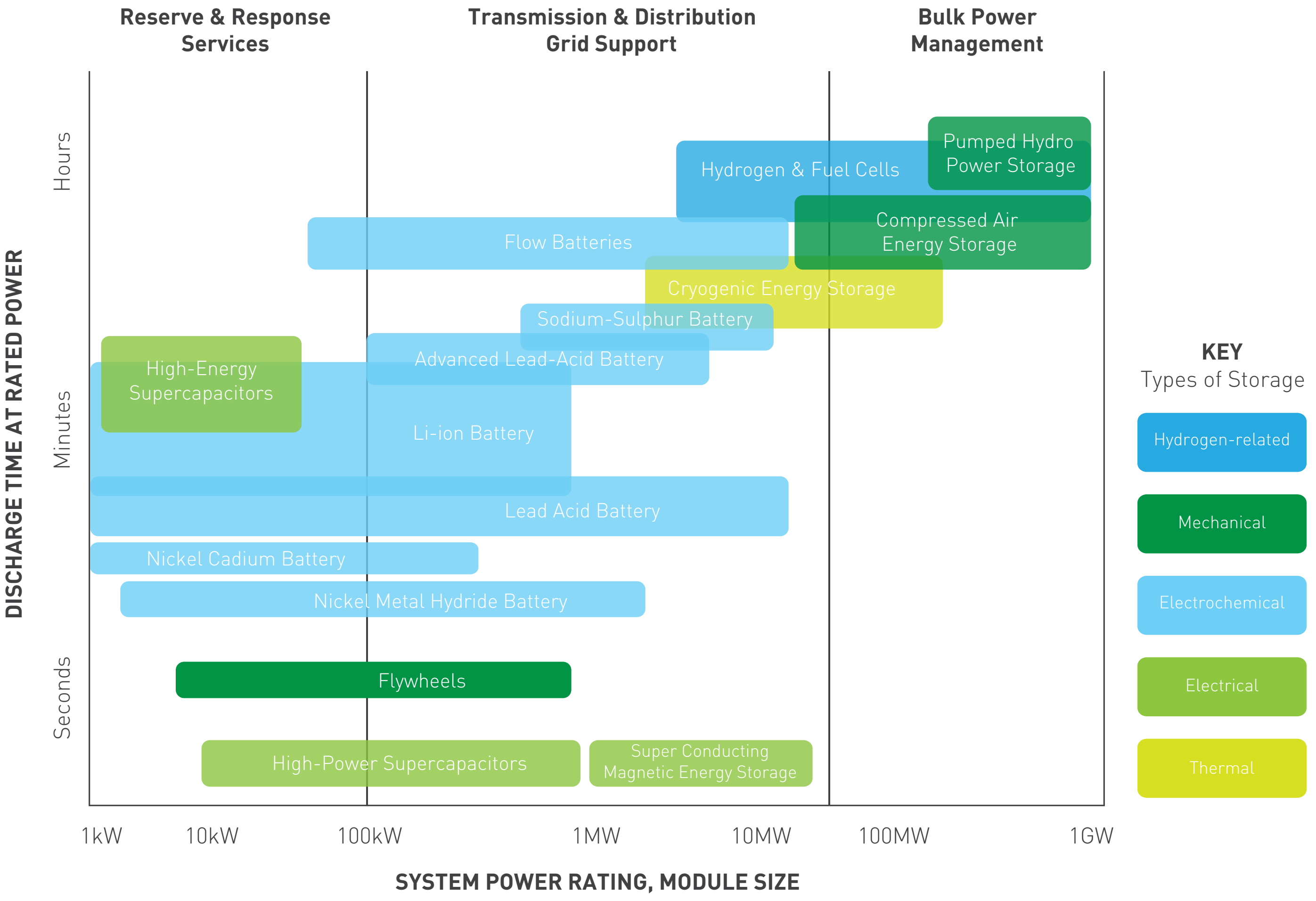


Figure 3.1: Suitability of different EES technologies for grid-scale applications.
Notes: The figure is intended for conceptual purposes only; many of the options have broader duration and power ranges than shown.

Batteries of different chemistries provide flexible options that can be used at scales from a kW up to several MW, making them suitable for a wide range of applications from the household level up to utility scale. In the longer term EV/hyrbrid electric vehicle (HEV) batteries that are no longer suitable for use in vehicles may provide a low cost source of small-scale energy storage. This lengthens the usable lifetime of the battery pack and gives inherent value to the pack in a 'second life' application. As an example, it has been found that in some cases HEV batteries have only lost 20% of their capacity by the time they are being sent for recycling, leaving 80% of useful capacity being wasted. This could be utilised in distributed storage solutions.

Another form of flexibility is provided by CES, which can decouple the location of charging and discharging through the use of transportable tanks.

Other considerations

Most EES technologies have obvious cost advantages in one aspect at the expense of another, for example supercapacitors and flywheels are the most expensive EES in terms of energy storage capacity but the cheapest in terms of power capacity. Conversely PHS and CAES are the cheapest in terms of energy storage but among the more expensive in terms of power capacity. Since PHS and CAES have limited scope for deployment, other technologies are also of interest for bulk storage. Lead-acid batteries provide a mature solution with similar cost per kWh – albeit with a reduced lifetime – and CES and fuel cells promise similar price points and lifetime in projected figures.

While PHS clearly has the longest potential lifetime of the considered technologies, a lifetime comparison quickly reveals a pattern at the lower end of the scale in chemical-based storage systems. Chemical degradation has a significant impact on lifetime, although current research into recycling methods may mitigate the negative effect of this. Nevertheless, grid scale battery installations comprise exceedingly large and complex plant and many hundreds of thousands of cells; small gains in lifetime extension will give large benefits. The other electrical and mechanical-based EES systems all have comparable lifetimes.

CES is unique in that it can provide environmental benefits by removing contaminants in the air and CO_2 capture during the charging process. Some types of CAES involve fossil-fuel combustion, while some of the chemical-based EES mechanisms have potentially high environmental impact dependent on their exact chemical composition – there can be dozens of sub-types for a single technology. It is hoped that through improvements in recycling processes toxic waste can be reduced. Other considerations are the impact on landscapes by PHS systems, and the negative effect on human health associated with strong magnetic fields such as in SMES.

5. Spinning-reserve is currently often supplied by power stations which burn coal, gas, oil or other fossil fuels, and these are required to run below their rated capacity which further reduces overall system efficiency.

THERMAL ENERGY STORAGE TECHNOLOGIES

There are essentially three ways in which heat can be stored:[6]

SENSIBLE HEAT STORAGE: THERMAL ENERGY IS STORED AS A RESULT OF A CHANGE IN A MATERIAL'S TEMPERATURE. THE MOST COMMON MATERIAL USED IS WATER, BUT OTHER MATERIALS SUCH AS ROCK, SAND AND CLAY CAN ALSO BE USED.

LATENT HEAT STORAGE: THERMAL ENERGY IS STORED AND RELEASED AS A RESULT OF A CHANGE IN A MATERIAL'S PHYSICAL STATE (E.G. LIQUID TO SOLID AND VICE VERSA). MATERIALS THAT ARE USED TO STORE LATENT HEAT ARE TERMED PHASE CHANGE MATERIALS (PCMS).

THERMOCHEMICAL HEAT STORAGE: HEAT IS APPLIED TO CERTAIN MATERIALS TO PRODUCE A REVERSIBLE CHEMICAL REACTION AND THERMAL ENERGY IS STORED AND RELEASED AS THE CHEMICAL BONDS ARE BROKEN AND REFORMED.

Hot water tanks are probably one of the best known thermal energy storage (TES) technologies and are a fully commercial technology. They are already widely used at a building scale in combination with electrical or solar thermal water heating systems to store water over a number of hours from when it is heated (e.g. at night when electricity is cheaper or during the day, when the sun is shining) until it is needed. In the future it is possible that larger versions could be combined with heat pumps. At a larger scale, hot water storage can also be used in conjunction with CHP and district heating (DH) systems. Using thermal stores or accumulators allows the CHP-DH operator to optimise the fuel utilisation and load factor of a district energy scheme by generating electricity during peak periods and storing any excess heat which can subsequently be distributed when demand is high. The storage efficiency can be further improved by ensuring optimum stratification of water in the tank.

Larger storage volumes and longer storage periods (up to months) can be achieved by storing hot (or cold) water underground. Naturally occurring aquifers (e.g. a sand, sandstone, or chalk layer) are most frequently used. Groundwater is extracted from the layer and then re-injected at a different temperature level at a separate location nearby. There are also a number of projects worldwide that use underground storage in boreholes, in which vertical heat exchangers are inserted into the underground and thermal energy is then stored in the clay, sand, rock, etc. Boreholes are often used to store solar heat in summer for space heating of houses or offices. Another alternative is cavern or pit storage, in which large underground water reservoirs are created in the subsoil to serve as thermal energy storage systems. These storage technologies are technically feasible, but the actual application is still limited because of their high investment costs.

Sensible heat energy storage has the advantage of being relatively cheap, but the energy density is low and the efficiency can be low due to heat losses. To overcome those disadvantages, phase change materials (PCMs) are being explored for thermal energy storage applications. The PCM could be included in containers as a standalone store or be included in building materials, so storing solar energy during the day and the cold during the night. Suitable PCMs would ideally need to meet a number of criteria including the ability to release and absorb large amounts of energy when freezing and melting, have a fixed and clearly determined phase change temperature, remain stable and unchanged over many freeze/melt cycles and be non-hazardous.

Thermochemical storage is another option that provides a number of advantages compared to storing hot water. These include smaller storage volumes due to the higher energy storage density and, in principle, no thermal energy losses even for long storage periods. The economics of this approach are still uncertain, but there should be the potential for R&D to improve performance and to reduce costs through mass production (Lottner and Mangold, 2000).

	CAPACITY KWH/T	POWER MW	EFFICIENCY (%)	STORAGE TIME	COST $ CENT/KWH
HOT WATER	10 - 50	0.001 - 10	50 - 90	day - year	0.01
PCM	50 - 150	0.001 - 1	75 - 90	hour - week	1 - 5
CHEMICAL REACTIONS	120 - 250	0.01 - 1	100	hour - day	0.8 - 4

Table 3.2: A comparison of different TES technologies. Source: Hauer (2011)

The choice of a thermal storage material will depend on the application and will involve finding the most appropriate combination of energy storage temperature, charge/discharge rates, energy storage density, storage duration (hours, days, months), round trip efficiency (what fraction of energy comes out at a usable temperature), durability (number of charge/discharge cycles possible over design life) and cost effectiveness.

R&D EFFORTS AND NEEDS

The further development of both electricity and heat storage technologies will be important for all applications, from large-scale generation and grid ancillary services all the way down to customer and end-user sites. For some of the smaller and scalable technologies – such as batteries, fuel cells, super-capacitors, and flywheels – demand from the transport industry is spurring parallel research efforts, which will serve to reduce the time to commercialisation and increase the rate of technical developments.

Some of the most important and promising areas for further R&D efforts include:

- Safety issues surrounding electrochemical storage systems; in particular high temperature molten metal batteries, for example sodium-sulphur.
- Reduction in costs; for example, vanadium redox storage batteries are very expensive.
- Extension of the useful operating lifetime of all of the battery storage systems would be advantageous, but significant work could be carried out into the cycle life issue surrounding deep discharge operation of the cheaper and more easily recyclable batteries, such as lead-acid chemistries.
- The prediction of lifetime and available energy in battery storage systems needs to be urgently addresses to tackle issues surrounding 'fuel gauge' insecurity for energy storage systems; for example, research into battery modelling and accurate state of charge and state of health prediction algorithms.
- The newer battery chemistries, in particular sodium-ion and lithium-air batteries which need further research to mature the technology.
- Advanced thermal and cryogenic energy storage systems would also benefit from further work to extend their operating ranges and usability.
- There is also a need for more research looking at the integration of EES into systems from grid scale to end-users and the relationship with broader developments in smart grids.

CONCLUSIONS

There are many different technologies that can provide heat or electrical storage at different stages of maturity and with a wide range of technical characteristics. It is unlikely that a single solution will emerge in the near (or perhaps even distant) future given the wide variations in possible applications.

To date the push towards energy storage is from companies wishing to provide load levelling and frequency response correction with higher power/energy, centralised systems. Pumped storage and CAES are both commercial technologies that can provide long-term large scale storage and may be joined by flow batteries, hydrogen and CES in the longer term. Where fast response is required then flywheels are currently commercial, but supercapacitors also offer interesting prospects. However, there appears to be growing interest in decentralised, or distributed, EES systems which may have significant advantages, as discussed elsewhere in this report.

For these applications, a wide variety of battery technologies may have a role to play, of which lead-acid and nickel and sodium-sulphur are most likely near term choices, with metal-air holding longer-term promise. The use of second-life lithium-ion batteries could also be an interesting option if EV/HEVs start to take significant market share. Heat storage is another area that has not traditionally received much attention.

However, if heat storage could be made available locally, there could be a significant reduction in the amount of energy required to be distributed around the electricity system, therefore a variety of heat storage technologies, including those using novel materials, are also worth investigating further.

6. This section is significantly based on information from the website of the IEA Implementing Agreement, Energy Conservation through Energy Storage (www.iea-eces.org).

4: ELECTRICITY MARKETS, REGULATION AND RELATED ISSUES

This section explores some of the most important market and regulatory issues that are likely to affect the deployment of energy storage in the UK, with a particular focus on electricity.

In theory there are three broad areas of opportunity for energy storage in any electricity system:

- **Providing short-term reserve and response services:** this helps the system operator to maintain a real-time balance between supply and demand across the system.
- **Enhancing the utilisation of existing assets:** depending on its location on the networks energy storage can displace additional back-up generation capacity and avoid investment in network reinforcements.
- **Engaging in arbitrage by storing electricity when it is cheap and releasing it when it is more expensive:** in a system with high levels of variable generation this can even out peaks and troughs, thus helping to integrate renewables into the system more effectively.

As noted earlier in the report, storage can be located at different points on the network from generation, through transmission and distribution to demand. The optimal choice can be strongly influenced both by the services that the storage system is required to deliver and by the particular market and regulatory environment. The following sections explore the use of energy storage at the high voltage transmission and medium/low voltage distribution levels.

GENERATION AND TRANSMISSION

The current electricity market arrangements, known as The British Electricity Trading Arrangements (BETTA), were established in 2005 and cover Scotland, England and Wales (Figure 4.1).[7] The market is now dominated by six large vertically integrated companies (they own retail and generation licences, and sometimes also distribution and transmission licences) who use long-term contracts and a bilateral trading facility to agree the sale and purchase of most of the electricity ahead of when it is actually generated and delivered.[8]

After 'gate closure' (one hour before delivery) the system operator (SO), National Grid, has the responsibility to ensure that there is a match between supply and demand by operating the balancing mechanism. It does this by having separate contractual arrangements in place for the necessary reserve and response services, which give the system operator some flexibility in the event that the predicted levels of generation and demand are not completely accurate. Although limited in volume, pumped storage provides a useful option that is available to meet short-term peaks and to provide other response services (e.g. maintaining frequency).

7. Northern Ireland has separate arrangements. It is part of the Single Electricity Market for the island of Ireland, together with the Republic.

8. As a result, less than 5% of electricity is traded through the balancing mechanism.

Looking to the future, it is likely that developments in the electricity market and wider energy system will make the role of the SO more complex. There are two key areas where such developments will have an impact (Gross et al., 2006) – 'reliability' impacts and system balancing impacts – both of these are relevant to storage. The first is that increasing levels of variable electricity generation (such as from wind turbines) will cause wider variations in output (independent of demand) than has previously been the case. The use of large-scale storage systems associated with particular generation assets, or connected to the high-voltage transmission system, could smooth the output from variable sources by acting as both a supply and demand for electricity. So storage could provide additional generation to back-up variable renewables at times when they are not able to operate at full capacity to meet demand. Storage could also absorb excess generation at times when it exceeds local demand, so avoiding the spill/curtailment of generation, thus increasing the overall load factor of renewables, and/or offsetting the need for additional transmission investment to meet the peaks. However, the current economics of energy storage in this role in the UK are not particularly attractive for a variety of reasons, for example:

- high capital costs and low load factors;
- high network charges imposed on storage operators (e.g. storage operators have to pay Balancing Services Use of System Charges when they take or supply electricity, even though it may contribute to balancing the system); and
- the structure of the Feed-in Tariff, which rewards generator output regardless of the costs it imposes on to the system, so there is little incentive for generators to invest in storage.

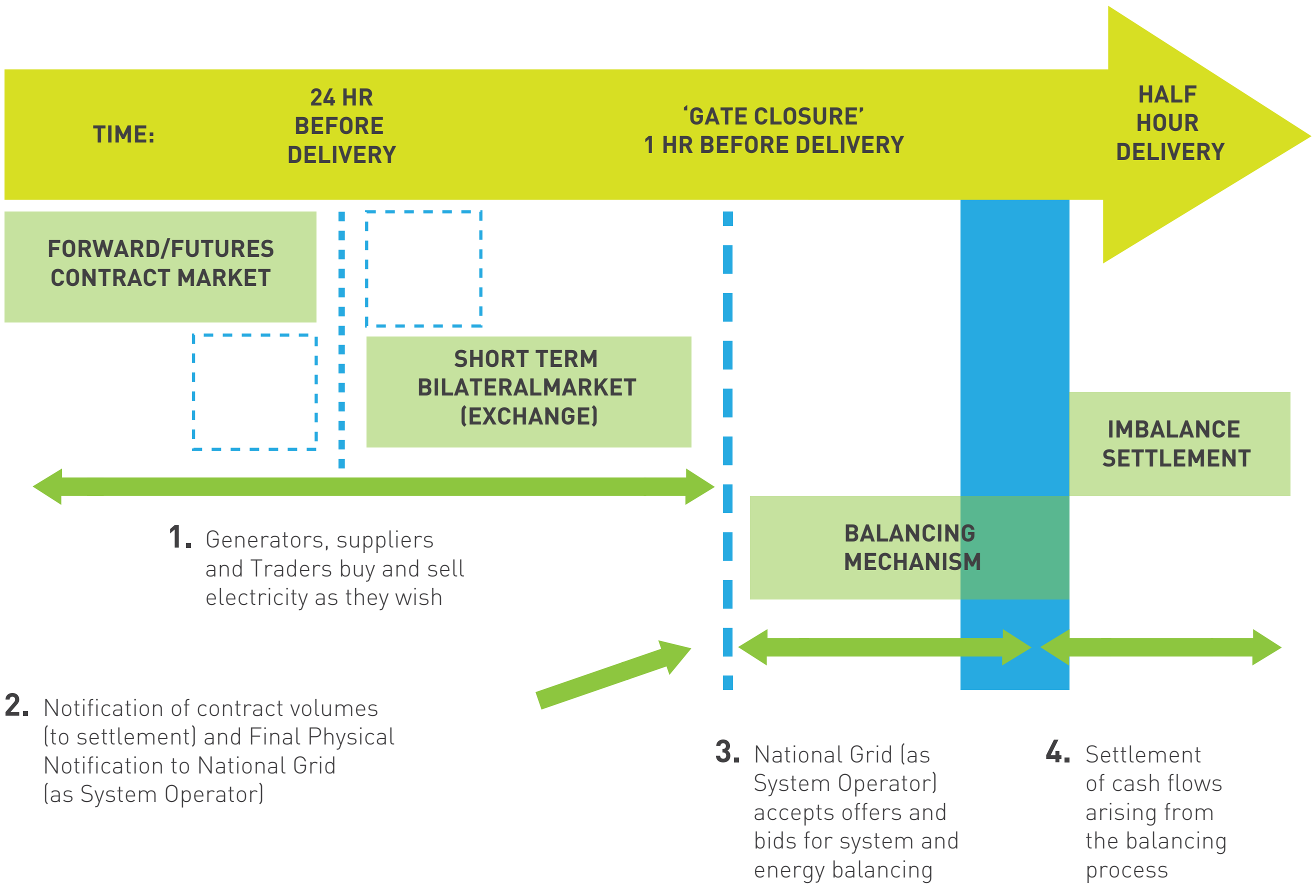


Figure 4.1 The British Electricity Trading Arrangements.
Source: National Grid (2011a) - © 2011 National Grid plc, all rights reserved.

A greater role for energy storage would be likely in an energy system consisting of a high penetration of variable renewable energy (increasing load factors) and lower investment costs, even if this was at the expense of efficiency. For instance, Grünewald et al. (2011) find that large-scale energy storage starts to provide a positive return in a system with around 40 GW of installed variable renewables.

The more immediate concerns for the system operator are the short-term system balancing impacts of variability. In its role as residual balancer, the SO will need to expand and develop its portfolio of response and reserve services in order to manage short-term fluctuations in the system. National Grid (2011b) estimates that, under a scenario with around 25 GW of transmission connected wind generation capacity by 2020 (operating with a 30% load factor), the operating reserve requirement will need to increase from the current 4 GW to around 7 GW.

In order to manage the short-term fluctuations on a system with high levels of variable generation and meet the projected gap in reserve, it is likely that the SO will consider a number of different options. These will potentially include increased back-up capacity, greater interconnection capacity, more demand response (DR) and increased storage capacity (Figure 4.2). It is unlikely that any one of these solutions will be sufficient as each has their advantages and disadvantages (Table 4.1) and an optimal mix of balancing solutions is likely to include some proportion of all of the above, including storage, with an emphasis on those technologies that can offer fast response (possibly at the expense of long storage durations).

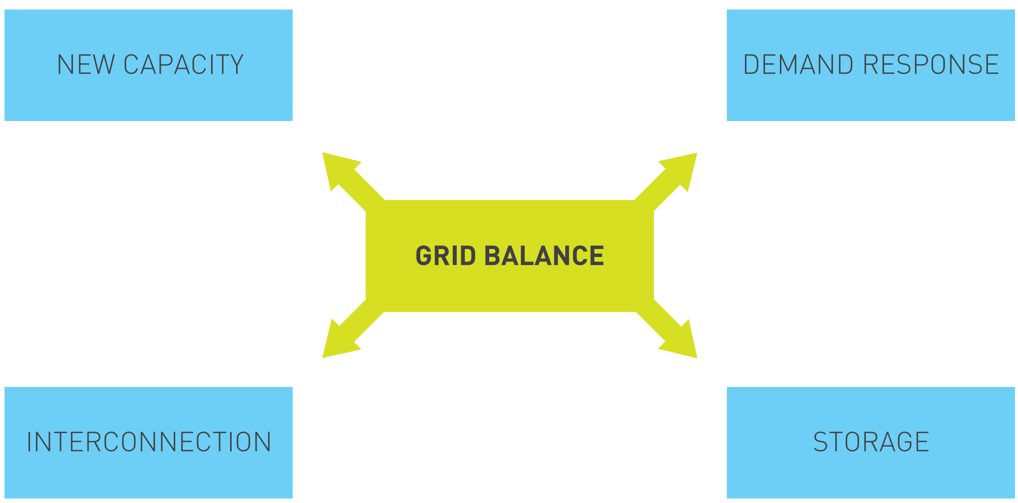


Figure 4.2 Options for network balancing.

OPTION	ADVANTAGE	DISADVANTAGE
STORAGE	• Diverse set of technologies which can provide multiple services e.g. fast reserve, frequency response and black start • Can be deployed at all scales of the system • Short construction times (if decentralised) • Provides system wide benefits (discussed below)	• Some technologies unproven and lack demonstration • Regulatory and market barriers to some applications • High upfront costs for some technologies
INTERCONNECTION	• Proven technology and facilitates market integration with EU • Can relieve constraints on the transmission networks	• Relies on a price differential between markets • Similar weather systems are often spread across the UK and neighbouring markets, so cannot always be relied upon during periods of low wind (Pöyry, 2011) • Long construction times and uncertain investment climate (Meeus et al., 2006)
DEMAND RESPONSE	• Arrangements already in place for large industrial loads. This can be expanded (National Grid, 2009) • Significant scope from domestic consumers, facilitated by smart meter role out and time-of-use tariffs (Ofgem, 2011)	• Potential and cost for wide scale domestic DR is largely unproven • Market for services is immature
NEW CAPACITY	• Flexible and provides a wide range of services • Proven technology with a positive investment climate	• Lower load factors in the future may impact economics • No opportunity for arbitrage • Peaking plant is typically high(er) carbon OCGT • Can't help avoid curtailment of variable renewables

Table 4.1 Characteristics of different balancing options.

Electricity Market Reform (EMR)

In 2011 the Department for Energy and Climate Change (DECC) published a white paper (DECC, 2011b), which sets out proposals to change aspects of the electricity market in order to attract private sector investment in various low carbon generating technologies. One of the proposals is for a new Capacity Mechanism, which is intended to ensure continued security of supply and incentivise investment in the different options listed in Table 4.1.

To date, ensuring security of supply has largely involved securing a balance between supply and demand in the short-term as sufficient capacity had been built into the system during the nationalised era and the early years of privatisation. National Grid has successfully operated a capacity market to deal with these short-term issues. However, as old generating stations are decommissioned or reaching the end of their lives and greater levels of variable renewables come onto the system, there is a growing concern that the current capacity market will not provide a significant long-term incentive for investment in new capacity. A follow-up document (DECC 2011c) outlined that the Government will receive advice from both Ofgem (the regulator) and the SO on the required volume of capacity a number of years in advance and, based on these estimates, the relevant minister will initiate an auction process 'for the required volume of capacity needed to deliver security of supply' (ibid: p.4) which is run by the SO. The successful providers will receive 'availability payments' for the provision of capacity on demand to the SO (ibid: p.23).

There is no separate treatment for storage under these proposals and so generation, interconnection, demand response and storage providers will compete against each other for the contracts. While the Capacity Mechanism would allow storage to compete in other markets, it seems probable that the mechanism will favour established solutions, such as flexible gas-fired generators, and perhaps a limited increase in pumped storage, as these are the most commercially viable under current conditions.[9] However, the Capacity Mechanism as currently planned would not reward the wider system benefits that storage (and perhaps some of the other options, such as demand response) is able to provide (Box 4.1).

A recent analysis for the Carbon Trust has calculated that energy storage can have significant value to the electricity system in 2030, even when compared against back-up generation, greater interconnection and more flexible demand response (Imperial College, 2012). The problem is that these benefits are spread across the value chain, from generation, through transmission to distribution, and it may be too expensive for any discrete part of the value chain to realise a sufficient return on investment.

IMPROVE ASSET UTILISATION OF RENEWABLES: IN A HIGH WIND SCENARIO IT IS POSSIBLE THE SYSTEM WILL BE UNABLE TO ACCOMMODATE ALL OF THE WIND ON THE SYSTEM (PARTICULARLY IF IT IS GEOGRAPHICALLY CONCENTRATED). THE ABILITY OF STORAGE TO BOTH ABSORB AND INPUT POWER INTO THE GRID MEANS THAT IT CAN EVEN OUT THESE FLUCTUATIONS IN OUTPUT AND AVOID THE CURTAILMENT OF RENEWABLES WHEN DEMAND IS LOW.
LESS TRANSMISSION AND DISTRIBUTION NETWORK INVESTMENT: THE CURRENT APPROACH TAKEN BY NETWORK OPERATORS TO ALLEVIATING CONSTRAINTS ON THE TRANSMISSION AND DISTRIBUTION SYSTEMS IS TYPICALLY TO REINFORCE THE NETWORKS. UNDER CURRENT GRID CODES THE GRID MUST HAVE ENOUGH CAPACITY TO MEET PEAK (RATHER THAN AVERAGE) DEMANDS. OFFSETTING SOME OF THIS INVESTMENT WITH STORAGE COULD POTENTIALLY REDUCE THE COSTS TO THE CUSTOMER OF NETWORK REINFORCEMENTS.
LESS DEMAND FOR PEAKING PLANT: CONVENTIONAL PEAKING PLANT IS TYPICALLY PROVIDED BY OPEN CYCLE GAS TURBINES. OFFSETTING THE REQUIREMENTS FOR PEAKING PLANT BY USING STORAGE CAN REDUCE OVERALL CARBON EMISSIONS.

Box 4.1: Benefits of energy storage to the grid.

Thus, while the current proposed changes to the electricity market may provide some incentives for new storage capacity, the business case may be dependent on generating revenue streams from a number of different functions, potentially leading to high transaction costs from putting in place a complex set of contracts.

DISTRIBUTION AND THE DEMAND-SIDE

As discussed earlier, the majority of storage used in the UK today is at large scale pumped hydro sites deployed by the system operator in order to balance the grid and provide a range of system services. Despite its early application in urban DC electricity systems (Schallenberg, 1981), more recently there has been little deployment of smaller scale, decentralised storage devices in the UK.

There are three main reasons for this:

- Firstly, the development and expansion of energy infrastructures during the latter half of the 20th Century was based on a 'predict and provide' philosophy where enough capacity was built in order to accommodate growing demand. This resulted in the construction of large capacity margins with little need for active management of distribution systems or the demand side; therefore little need for storage at this level of the system.
- Secondly, during the early years of privatisation in the UK, the newly privatised energy companies undertook a major investment programme in gas-fired combined cycle gas turbine plant due to the abundance of North Sea gas and the advantages that flexible and efficient plant had in the context of liberalised electricity markets. This inherent flexibility offset the need for any form of decentralised storage.
- The third main reason has been the regulatory arrangements in the UK, which treat storage as generation. Therefore, due to the unbundling or separation of natural monopoly networks from the competitive market segments, network companies – distribution and transmission – cannot benefit from using energy storage in the trading environment. Although it may have some benefit to distribution companies to ease constraints (thermal/voltage) and potentially to offset or postpone network reinforcements, this option has typically not been taken up by distribution network operators (DNOs), partly due to the costs and risks of storage solutions compared to conventional reinforcements, but also due to a conservative approach to network planning and operation which has been reinforced under the current regulatory regime (Bolton and Foxon, 2011).

Despite these barriers and the lack of experience with integrating storage systems into the distribution network, there is some evidence of DNOs becoming more interested in examining the benefits that storage has to offer as part of a trend towards 'smart grids'. One source of funding for demonstration projects is the Low Carbon Networks (LCN) Fund, an innovation incentive for DNOs introduced in 2010 as part of Ofgem's fifth distribution price control review to run over five years. The LCN fund is a smart grid demonstration incentive directed at distribution network operators who are seen as potential key players in the transition towards smarter grids. The competitive fund consists of Tier One (total of £80m), for smaller projects, and a larger Tier Two fund (of £320m) for 'flagship projects'. Table 4.2 lists a selection of the projects funded to date under the LCN fund which have a storage element.[10] The application of storage in the LCN projects is still relatively low however, particularly in the larger Tier Two projects.

Energy storage and the distribution system operator

What the LCN fund examples show is that there is a wide range of applications for energy storage at this level of the system and in the future there are likely to be further opportunities. However, the deployment of storage at the distribution level would be helped by changes to the way networks are regulated. One example that is often mentioned is to change the current role of a DNO to that of a Distribution System Operator (DSO). Under such an arrangement the SO would delegate some or all of its responsibility for maintaining the networks at a regional level to the DSOs. These DSOs would then be able to procure third party ancillary services (e.g. local generation and demand-side management) to balance their networks at a regional level. DSOs would also be able to utilise technologies such as energy storage to balance the regional system (EA Technology, 2010).

Such developments could provide a stimulus for the deployment of meso and micro-scale storage technologies to relieve congestion on distribution networks and trade in the balancing markets. It would also offer the opportunity for DSOs to combine the use of decentralised storage with demand response measures in a synergistic way, to optimise the operation of their existing asset base. However, the evolution from a conventional asset manager business model to a DSO that is a more active market participant would require the current DNOs to evolve into more innovative businesses. It would also most likely necessitate changes to the current rules at the UK and EU levels surrounding unbundling and market structure.

9. The Government had also considered a 'Strategic Reserve' instead of a Capacity Mechanism, but this may have been less favourable to storage as it would have not been able to generate revenue streams from other functions, such as arbitrage.

10. http://www.ofgem.gov.uk/networks/elecdist/lcnf/pages/lcnf.aspx

PROJECT NAME	DNO	DESCRIPTION
TIER ONE PROJECTS		
ORKNEY ENERGY STORAGE PARK	SSE	A project to create contracts and conditions to allow third party 'Energy Storage Providers' to manage network constraints on the Orkney distribution system.
1 MW BATTERY, SHETLAND	SSE	A $1MW_e$ battery will be connected at the Lerwick Power Station on Shetland. This will be integrated with local DR in order to smooth station peaks and provide additional demand capacity. The aim is to manage network constraints.
'DEMONSTRATING THE BENEFITS OF SHORT-TERM DISCHARGE ENERGY STORAGE ON AN 11KV DISTRIBUTION NETWORK'	EDF/UK Power Networks	This involves a Li-ion storage device in Hemsby, North Norfolk. This project is designed to test existing simulations by running experiments on the device with different seasonal, load and generation output variations.
TIER TWO PROJECTS		
BUILDINGS, RENEWABLES AND INTEGRATED STORAGE, WITH TARIFFS TO OVERCOME NETWORK LIMITATIONS (B.R.I.S.T.O.L.)	WPD	The project will implement DR measures to help the DNO manage stresses associated with low carbon technologies and to allow for the deferral of reinforcements and renewables integration. It involves storage technologies and DC networks and is based around supplying modified ICT equipment and DC lighting in the Bristol area. The project involves the application of battery storage technologies.
NEW THAMES VALLEY VISION (NTVV)	SSE – Southern Electric Power Distribution Ltd	Project based in Bracknell. Photovoltaics, advanced smart metering and storage devices will be connected; this is designed to replicate a system with diverse low carbon loads. Sensors at substations will monitor the network. Storage will be deployed at LV substations, street cabinets, and in households. 3 x 500 kWh, 12 x 50 kWh, and 50 x 10 kWh batteries to be installed.
FALCON	WPD	In order to remove constraints on an 11kV network, storage technologies will be trialled as one of six ways to reduce peaks. Batteries to be installed at secondary substations on the LV side of the transformer. 30 sodium metal halide batteries deployed across five secondary substations will be involved in the trial area.

Table 4.2: A selection of projects involving storage under the Low Carbon Networks Fund.

Thermal storage with CHP-DH

Another example of the application of energy storage at the distribution level is the use of thermal storage alongside decentralised CHP-DH. This typically consists of a gas-fired generation plant which produces electricity but, unlike a conventional centralised plant, the heat produced during the conversion process is not wasted, rather it is distributed locally as steam or hot water using a network of distribution pipes. Using thermal stores or accumulators allows the CHP-DH operator to optimise the fuel utilisation and load factor of a district energy scheme by generating electricity during peak periods and storing any excess heat which can subsequently be distributed when demand is high.

Also, if electricity prices reflect demand during different periods, there is potential to use cheap electricity for storing and distributing heat. In Demark this technique has been utilised to create a synergistic relationship between an electricity system with high levels of intermittent wind power and local heat supply systems. During periods of high wind, when supply is greater than demand, CHP-DH operators can use this cheap power to store and distribute heat. This approach has had a limited application in the UK but, given moves towards a low carbon energy system with biomass and waste to energy and CHP becoming more common, such thermal stores could be used to displace expensive and high carbon gas-fired back-up plant by smoothing hourly and daily demands.

Demand-side storage

Changes in the wider energy system, coupled with an evolving regulatory structure, could see micro-scale storage technologies being deployed at the level of individual households. Storage applications as part of such a smart grid could include V2G technology – while vehicles are stationary their batteries could be used for arbitrage similar to conventional storage technologies – small scale domestic batteries or thermal storage using phase change material. It seems probable that in order for such a complex disaggregated system to work effectively a new type of energy storage aggregator business model would be required to trade in the electricity markets on behalf of customers.

CONCLUSIONS

Energy storage plays a small but important role in facilitating the smooth operation of the current electricity market. In the future, a trend towards greater deployment of variable renewables for electricity generation combined with more use of electricity for heating and transport is likely to mean that energy storage can offer further benefits across the value-chain. The need for reserve and response capacity may almost double in the period to 2020 and increase even more rapidly towards 2030 and beyond (several tens of GWs). This suggests that storage could have a substantial market in the future, not only in terms of its traditional role in system balancing at the transmission level, but at the distribution and customer side where it could potentially be of most value by reducing the costs of decarbonising the energy system.

If energy storage is to play a major role in a future electricity market then it will need to overcome a number of market and regulatory barriers. Firstly, storage technologies may be too expensive for any discrete part of the value chain to realise a sufficient return on investment. This issue may be further complicated by the fact that some of the markets in which storage can offer services are open to competition, while others are regulated. While the proposals for a new capacity mechanism under the EMR offers the opportunity for a potentially valuable revenue stream for storage in the UK, it is unclear as to whether the system-wide benefits of storage (and DR) will be adequately rewarded. National Grid has acknowledged that further work is needed on how the benefits of storage 'may be shared across the value chain and the term on which returns on investment are considered' (National Grid, 2011b: p. 85).

Secondly, under the current regulatory arrangements network companies cannot own and operate storage as it is treated as a generation technology. It is questionable whether storage should be treated as generation due to its ability to both absorb and input power and its potential to relieve congestion on the grid. A review should be undertaken to explore the advantages and disadvantages of treating storage as a regulated network asset that can be owned and operated by a transmission network operator (TNO) or a DNO. This could include an analysis of the use of storage under different market structures.

Thirdly, storage has the greatest value to the system when placed closest to the source of demand. This indicates that buildings-level energy storage could be attractive, including potentially heat storage if suitable regulatory and business models could be found that met both the needs of network operators and consumers.

5: PUBLIC ATTITUDES TO ENERGY STORAGE[11]

Current and emerging energy and environmental policy goals will imply significant changes to the entire UK energy system. In particular, decarbonising those systems – while ensuring secure and affordable supply – will have major ramifications for the public, as they are asked to accept new energy infrastructure and technologies and to change patterns of demand.

WHY PUBLIC ATTITUDES TO NEW ENERGY TECHNOLOGIES ARE IMPORTANT

Understanding public attitudes to these changes, and the ways in which energy and technologies are themselves understood and used, is important for a number of reasons. These reasons are commonly classified according to whether they are instrumental[12] or normative (value-based). On the instrumental side, such reasons include use of such understanding to help reduce ignorance and misunderstanding; raise scientific literacy; increase trust in scientists; mobilise favourable attitudes to scientific and technological innovation (including reducing objections to new infrastructure); change behaviour; and also so that public perceptions may be used in providing oversight of, and legitimacy to, technological innovation with potentially risky outcomes. On the normative side, members of the public arguably have a right to influence decisions about research, technology and policy that may affect them. This line of thinking is commonly based in notions of 'deliberative democracy.'

CHARACTERISTICS OF PUBLIC ATTITUDES TO ENERGY TECHNOLOGIES IN GENERAL

Distilling the literature on public attitudes to and engagement with energy, a number of interlinked themes can be identified, most of which also apply to non-energy issues and technologies:

- **Attitudes are influenced by context and are contingent:** this means that attitudes to the same object can vary under different circumstances, some of which are referred to below.
- **Attitudes are influenced by how proposals and questions are framed:** this relates to both development proposals and to studies of attitudes. Particular framings are not right or wrong per se, but are more or less appropriate for the task at hand.
- **There are advantages and limitations of different attitudinal and behavioural measures:** large scale opinion surveys on topics about which people know little are of limited value for anticipating attitudes: they can indicate what people think but generally provide less information on why and also elicit attitudes that are likely to change.

11. As there is little to no readily available literature on the theme of public perceptions of energy storage specifically, the following sections infer from work on related energy technologies. Significant use is made of recent reviews of UK public attitudes to energy technologies and engagement in energy research (Upham, Whitmarsh et al, 2009) and (Whitmarsh, Upham et al, 2011). The reader is referred to these reviews for their extensive referencing, rather than citing heavily here.

12. The 'instrumental rationale' is based on the notion that stakeholders will 'like' and 'support' a decision more if they have been involved in the process by which it was made.

- **Timing (in respect of current events, R&D cycles, and policy implementation) is a critical consideration when measuring attitudes and planning engagement activities:** attitudes may vary along this cycle and moreover may be shaped by interactions of the public with the cycle. In the case of a local development, opposition may be engendered or amplified if people feel themselves unconsulted or uninformed of changes. In the case of an R&D cycle, waiting until roll-out before eliciting public opinion incurs avoidable risks. Note, however, that opinion may change through a long R&D cycle.
- **Public attitudes are heterogeneous and individuals play multiple roles in relation to energy:** attitudes vary across populations and, while people generally attempt to be attitudinally consistent across their roles as energy users and citizens, this is not always the case and behaviours and attitudes may not correlate well. In terms of demographic associations, generally, older people tend to be more conservative about change than younger people and women tend to be more risk-averse than men.
- **Energy use and technologies are socially embedded and are often taken-for-granted:** being socially embedded means that technologies influence behaviour and attitudes in ways that most people think little about in their everyday lives. Rather, they use those technologies in routine ways, following 'scripts' and habits that are learned and strengthened through repetition and which are resistant to change.
- **Public engagement with energy is influenced by social trust and institutional relationships:** energy issues are rarely viewed in isolation. People typically react not only to the attributes of a new technology, but in relation to issues such as their view of development in their locality, view of the local and national authorities and their trust in science and so on. Understanding the social characteristics of a locality is generally recommended when introducing a new development, energy-related or otherwise.

SPECIFIC ISSUES THAT MAY BE RELEVANT TO ENERGY STORAGE

Experience of other energy technologies suggests a number of plausible factors that may impact on public attitudes in the case of energy storage. These include:

- perceived risk (relating to toxicity, explosion, suffocation for example);
- perception of appropriate scale;
- proximity to a population;
- symbolism, cultural meaning and association;
- the distribution and scale of costs and benefits (of various types);
- perceptions of equity and due process;
- the degree of trust in any message sources;
- landscape context and value;
- utility and ease of use;
- fit with existing habits, routines and aesthetic perceptions;
- financing structures, compensation and ownership;
- the socio-economic and political context (employment levels and demographics of a locality and trust in relevant authorities, agencies and companies);
- the role and effectiveness of champions or opponents;
- the existence and success of contextual messaging (e.g. on climate change or energy security); and
- the wide variety of social norms (e.g. preferences in terms of mobility, communication, various fashions and so on).

Energy storage comprises a diverse range of technologies and technology scale serves as one way of exploring potential perception issues in more detail. At the larger scale, centralised storage systems may include cold water reservoirs for pumped storage, compressed air energy storage, flywheel systems and hot water reservoirs large enough to serve district heating systems. Decentralised systems at a domestic level may require a domestic user to purchase or install systems involving batteries or perhaps larger hot-water tanks. In between, at a medium scale, there may be versions of these capable of serving a community or neighbourhood.

Well-accepted energy storage technologies at the macro and meso-scales are likely to have several characteristics in common: the proposed funding method and consultation process would be seen as fair, perhaps with opportunities for a share in ownership at community level; consultation on siting would start early, with local dialogue, responsiveness to the concerns expressed and exploration of reasonable alternatives; consultation and engagement would aim to use small group discussions, engaging with existing social structures (e.g. parent and toddler groups, school groups, sports groups) rather than town meetings that tend to polarise; the locality would benefit in some way, perhaps financially or through provision of amenities; messaging would be at multiple levels, responding to different levels of comprehension, use of a range of media types and materials; discussion of risks would involve independent, trusted third parties, such as academics with no financial interest; public engagement and consultation would demonstrably go well-beyond legal compliance; 'unreasonable' opposition would be responded to and engaged with at an early stage in an attempt to limit amplification; the site would have appropriate social as well as technical characteristics, with this determined beforehand via discussion with local opinion-formers and others.

All of this requires adequate budgeting and the developers' arguments need to be genuinely and ethically defensible.

An optimal scenario for domestic scale storage technologies would likely be one in which there was a strong financial incentive to install a safe, convenient, quiet, aesthetically pleasing and fashionable, low maintenance technology, with the decision to install supported by trusted and social reinforced messaging (e.g. via association with major brands, celebrities and opinion formers). Current thinking on encouraging energy efficiency installation also applies here: installation may be encouraged via DIY and other store promotions, perhaps drawing on opportunities afforded by renovation, house moves, installation of conservatories etc.

If the system is visible to the user and lived with, it might ideally have 'plug and play' characteristics, with the engineering hidden and easy repair and installation. If the system is hidden (e.g. subterranean), installation would need to cause minimal disturbance or would ideally take place at the construction stage. Users would need to be convinced that their property price would not be adversely affected. While early adopters might be encouraged to trial and perhaps further develop the technology, reputational issues of immature versions of the technology would need to be avoided. In this regard, considerable effort may need to be spent to disassociate domestic versions from older, thermo-electric storage heater technology that many associate with poor controllability. Instead associations with technologically 'advanced but simple', environmentally benign and comfort should be sought. Of course these associations would need a justifiable basis.

CONCLUSIONS

Perceptions of energy storage can be considered in terms of issues categorised by technology scale, with the proviso that many of these issues do also apply across scales. Larger scale equipment may have industrial connotations, regardless of the nature of the end-consumer. Equipment out of sight, below ground or low level is likely to be preferable to infrastructure that draws attention. For this reason, little positive perception gain should be expected simply as a result of the infrastructure facilitating renewable energy use, unless there is close involvement of a directly benefitting community. This may be more plausible in rural locations with obviously-defined communities. In such cases, public engagement campaign should be an intrinsic part of the project. Conversely, there may be little that can be done to prevent opposition to storage infrastructure that people view as imposed on them, or which brings little obvious benefit to them. Similarly, siting in aesthetically sensitive locations will also increase the chance of opposition that may be difficult to reduce.

At the small scale of domestic or building-level devices, where homeowners need to live or work with a device, commission installation or self-install, then the technology needs to satisfy many of the criteria that are normally associated with consumer devices. This should be accounted for at the design stage. Affordability, controllability, performance, aesthetics and fit with the domestic or work habits will likely be important. Convincing consumers of this will require the development of mature and well-trialled storage technologies, followed by a variety of approaches to encouraging uptake.

Measures to encourage uptake are likely to include the precondition of either mandatory energy or emissions performance standards for residential buildings, or sufficiently high energy costs. Without a strong incentive to install, uptake will likely be low to modest. Moreover, the consumer will need to be convinced that, of the various energy-related options available, storage makes sense as an investment relative to other options. As even environmentally-conscious consumers find information in this field confusing, this issue of providing accessible information should not be underestimated. Given these preconditions, installation may be catalysed through demand stimulation measures, such as marketing and promotions in DIY stores and other retail outlets; enhancing market confidence through an installer certification scheme; and assistive financing through standard domestic energy billing e.g. energy service companies and measures such as zero interest repayment. In general the role of government in supporting and under-writing financing would likely be critical. Financing support also applies at the level of community-scale energy storage. Community champions and ownership/benefits issues are also likely to be important and there are models in the community wind sector that are relevant.

As very little is known about public attitudes to energy storage empirically there would be value in investigating some of the above propositions experimentally. At the macro and meso-scale this could include comparative investigation of existing analogous technology, such as underground water and gas storage, with the hypothesis that perceptions have relatively little to do with the particular purpose of the technology, and more to do with other attributes and associations. At the micro-level, much of the work before any large-scale roll-out would be similar to market research, with consumer pre-trial investigation in focus groups, followed by study of household experience in living with the equipment.

6: ALTERNATIVE PATHWAYS FOR THE DEPLOYMENT OF ENERGY STORAGE

Energy storage is not well represented in the majority of existing scenarios for the UK energy system (ERP, 2011 and Grünewald, 2011). To the extent that these scenarios consider energy storage at all, they largely focus on the role of bulk, centralised electricity storage, such as pumped storage. However, the previous sections have shown that, in reality, the range of potential applications and technologies for energy storage is diverse. Both electricity and heat storage could have an important role to play, over a wide range of scales.

To explicitly recognise the diversity of energy storage options that may have a role in the UK energy system to 2050, this section presents three contrasting socio-technical pathways for the deployment of energy storage. All the pathways are assumed to be consistent with the UK reducing its greenhouse gas emissions by 80% by 2050, from 1990 levels, in line with the Government's target, whilst also aiming to achieve energy security and affordability objectives. However, each pathway has deliberately distinct characteristics and in practice some combination of the three pathways is probably the most likely outcome. The three pathways are:

- **User-led storage:** household level heat and electricity storage
- **Decentralised storage:** distribution-level electricity storage and community heat storage
- **Centralised storage:** large–scale, bulk electricity storage with limited heat storage

The three pathways have been constructed using a step-wise approach (Figure 6.1). First, a narrative for the wider developments in the energy system is proposed. Secondly, the implications of these developments for balancing the grid and network constraints are considered. Lastly, a pathway for the development of energy storage is postulated as a solution to the issues identified in the first two steps, explicitly considering the co-evolution of technologies, institutions, user practices and business strategies.[13]

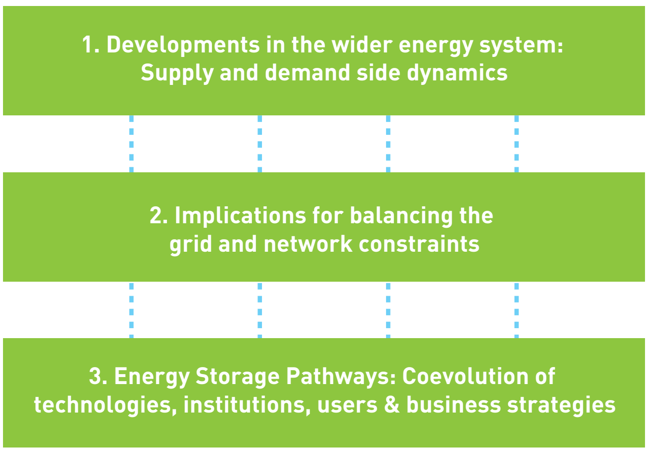


Figure 6.1 Structure of the pathways narrative.

13. This approach draws of the theory of co-evolution for analysing transitions to a sustainable low carbon economy as presented in Foxon (2011). The co-evolutionary framework explicitly recognises that a complex interaction of ecosystems, technologies, institutions, business strategies and social (user) practices impacts on low carbon transitions.

USER-LED STORAGE

The user-led pathway describes a scenario in which civil society plays a leading role in the governance of UK energy systems. This could be because individuals become convinced of the need to act on climate change and decide that neither central government nor market actors are likely to deliver sufficient action to keep the pathway on track to meet the 80% target.[14]

In this pathway, local bottom-up diversity of solutions flourish, with community leadership providing decentralised and micro-generation and energy conservation options. Energy supply companies roll-out smart meters and introduce innovative tariff structures which incentivise demand-side management and so individuals become more proactive and aware of their energy use. Associated with this trend, a range of microgeneration options including PV, wind and heat pumps are more widely deployed from 2015 onwards. Plug-in hybrid electric cars become widespread after 2020, followed by a more widespread take-up of electric cars which take significant market share from 2030 onward. However, these developments lead to constraints on the electricity networks during the 2020s, particularly on urban low-voltage distribution systems due to the clustering of technologies in certain locations.

Active consumers are seen as a resource that can address network constraints and help to offset expensive reinforcements. Initially consumers adopt a range of larger hot water tanks to act as heat storage for heat pumps (Figure 6.2). After 2025, the availability of cost-effective heat storage using phase change materials increases the heat storage capacity in larger dwellings. Vehicle-to-grid technology starts to be deployed from 2020 onwards to allow PHEV car batteries to be used for frequency stabilisation and other response services. After 2030, the trend in V2G technology accelerates as the recharging infrastructure is put in place with larger batteries in electric cars used as a more significant source of electricity storage. Some consumers also invest in battery storage units (including second-life batteries from PHEVs and EVs) to help smooth output from micro-generation systems and to act as a buffer between the grid and electric vehicle charging (thus avoiding peak electricity prices).

DECENTRALISED STORAGE

Under a decentralised pathway, meso-scale community and city based energy provision becomes a much more prominent feature of the UK energy system. This is driven by a localism agenda, which sees local authorities and local energy companies, or energy service companies (ESCOs), as best able to respond to the needs of customers and to address issues such as rising fuel poverty due to the costs of decarbonisation. This is incentivised by a significant uptake of the Feed-in Tariff, Renewable Heat Incentive and Green Deal schemes, which are coordinated initially by innovative local authorities and later this best practice spreads across the country. Once again, this leads to constraints on the medium and low voltage distribution networks due to voltage control and balancing issues and two-way flows.

Around 2015, it starts to become apparent that the uptake of electric heat pumps will not be as significant as originally thought due to a combination of technical issues, including the lack of space in many homes for significant heat storage. Meanwhile, technical advances in smart grid technologies and regulatory changes help DNOs take a more active role, blurring the distinction between transmission and distribution. By 2020 DSOs become key actors in the electricity system, taking over much of the system operator role within their regions currently carried out by National Grid. At the same time, central and local government provide incentives for the development of DH systems in urban areas and energy companies become much more involved in delivering heat as well as electricity. Both electricity and heat providers develop innovative business models and evolve into ESCOs.

Initially, the development and expansion of city-wide district heating schemes in a number of UK cities sees the use of thermal storage with CHP, allowing operators to optimise their plant (Figure 6.3). As DNOs begin to actively manage their systems they utilise this to help manage constraints. During the 2020s, following the success of the LCN fund and its successor in trialling a range of innovative electrical storage technologies – including lead-acid, nickel and sodium-sulphur batteries – innovative DNOs begin to integrate storage into their networks and reduce costs. This is facilitated by a new regulatory regime, which rewards innovation as a means of more effectively managing distribution networks with a range of decentralised technologies. During the 2030s, as best practice spreads across the sector, the development of smart grids gathers pace across the UK. This sees DSOs emerging as the key actors, enabling them to act as a platform for markets for decentralised energy services, e.g. storage provision.

14.The general direction of this pathway draws inspiration and shares some similarities with the 'Thousand Flowers' pathway presented in Foxon and Pearson (2011).

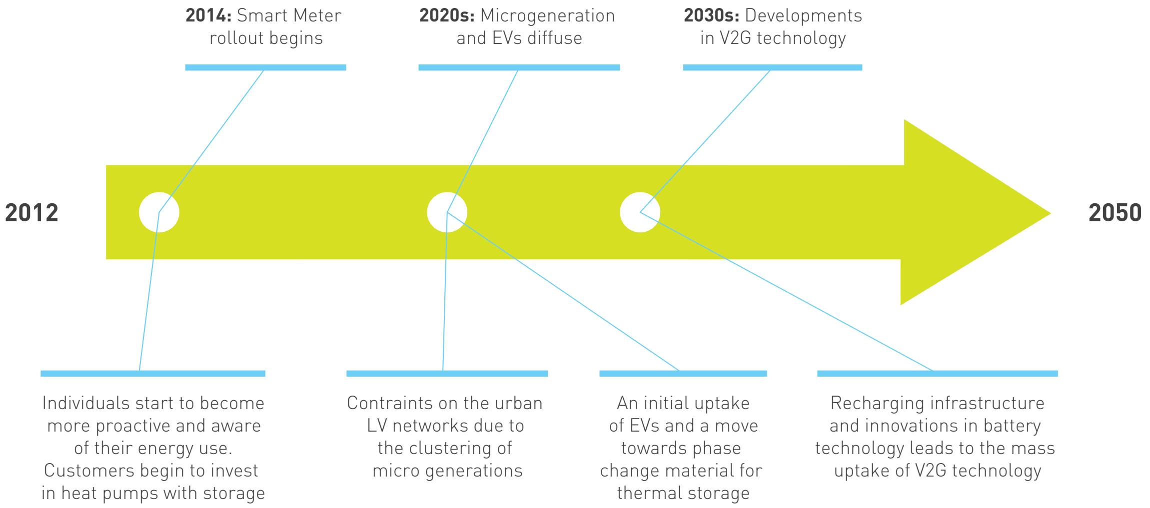


Figure 6.2: The user-led pathway for the deployment of energy storage.

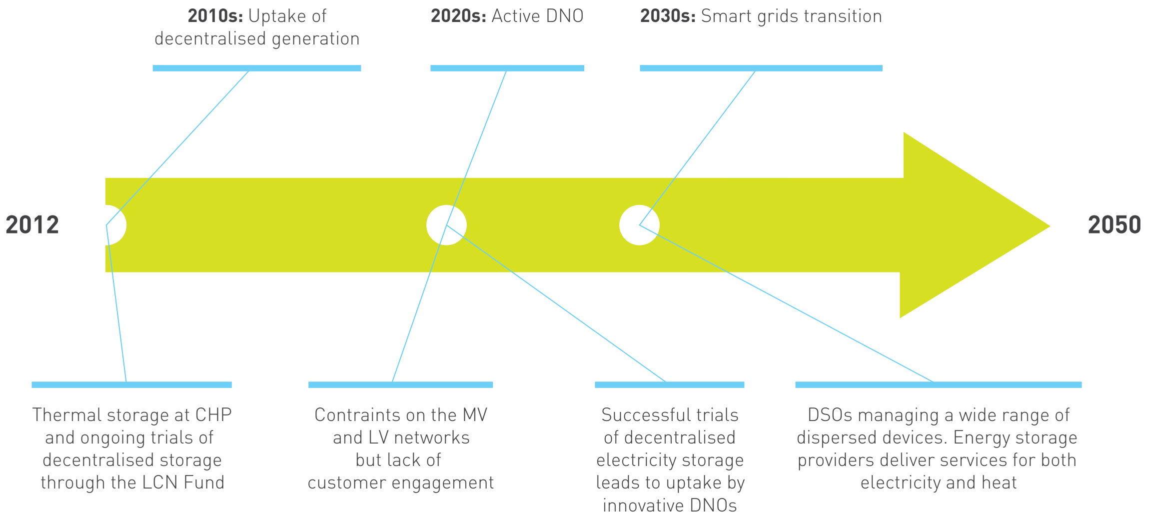


Figure 6.3: The decentralised pathway for the deployment of energy storage.

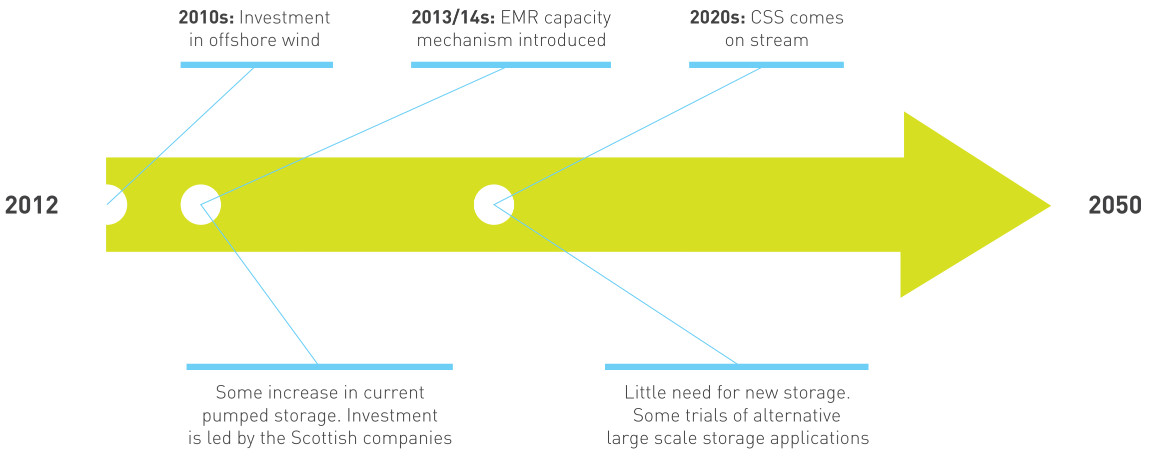


Figure 6.4: The centralised pathway for the deployment of energy storage.

CENTRALISED STORAGE

Under the centralised storage pathway, the current 'predict and provide' philosophy of energy system planning and operation prevails. The transition to a low carbon energy system is enabled by government providing the policy framework, within which private companies operate in a competitive market. This corresponds to the twin beliefs that only central government has the authority to drive the energy system to decarbonise at the rate necessary, and that the market is the most efficient way of delivering the outcomes according to the targets that have been set.

This pathway favours large-scale electricity generation with a rapid expansion of wind generation, particularly offshore, in order to meet the 2020 target of 20% of all energy produced from renewables. Facilitated by the introduction of a new capacity mechanism under the Electricity Market Reform, some new investments take place in pumped storage, for example at former small scale hydro plants in Scotland and there is some deployment of flywheels for frequency stabilisation (Figure 6.4).

The central role for National Grid as SO in balancing the grid remains as today and although the capacity of pumped storage increases, it retains a relatively small but important role in the management of the energy system. During the 2020s and 2030s, as CCS and new nuclear come on stream, there is little need for large-scale investment in pumped storage. However, some trials of compressed air storage, underground storage, CES and redox flow batteries receive R&D funding and there is interest in hydrogen as a longer-term option.

CONCLUSIONS

The purpose of these three outline transition pathways (summarised in Table 6.1) is to illustrate the broader energy system and social context within which energy storage may play a role in the transition to a low carbon economy. Each of these pathways presents its own risks and opportunities and, in order to realise them, strategic interventions will need to be made by both the Government and the regulator. For example, in the case of a user-led future, the manner in which the smart meter roll out can underpin and reinforce active customer engagement is key. The pathways also highlight the risks of an uncoordinated uptake of certain micro-scale technologies, such as electrical heat pumps, occurring without due regard to the implications this may have for the wider energy system. The potential for energy storage technologies to deliver necessary system benefits when required, however, may not be adequately recognised through short-term market mechanisms alone.

The decentralised storage pathway highlights the need to continue and expand incentives for research and development and technology trials, particularly those directed towards network operators who tend not to have a culture of innovation embedded in their organisations. Thinking about long-term efficiencies in this way will help to develop the capacity for both the organisational and technological flexibility, which will be required to deal with the uncertainties inherent in all of the pathways. The timing and nature of government and regulatory interventions will be key, and each of the coevolving factors considered in the table below – technologies, business strategies, users and institutions – need to be consider in a holistic fashion.

PATHWAY	TECHNOLOGY	BUSINESS STRATEGIES	USERS	INSTITUTIONS
USER-LED	Domestic level thermal storage and V2G, second life batteries	Innovative retail companies engage with customers	Active customers participate in and drive the energy transition	New tariff structures facilitate active customers and DSM
DECENTRALISED	Thermal and electricity storage embedded on the distribution grids	DNOs and innovative local authorities are key actors in system transformation	Users have a more passive role as individuals; less uptake of DSM and micro generation	Changes to regulations to facilitate DSOs
CENTRALISED	Large scale electricity storage on the transmission system	Lack of innovation; business as usual	Passive users; sector is dominated by incumbents	EMR capacity mechanism stimulates some storage investments

Table 6.1 Summary of the pathway characteristics.

7: INTERNATIONAL DEVELOPMENTS IN ENERGY STORAGE

This section briefly outlines some key activities being undertaken by other major countries and regions in research, development and demonstration (RD&D) and other policy support for energy storage technologies. The review includes China, the European Union and selected European countries, and the US.

The aim is to place UK developments in an international context and so draw comparisons and lessons that can help inform the UK's approach to energy storage.

The RD&D and policy activities described below vary but common themes include a focus on the storage of electricity (over storage of heat); a focus on battery technologies (over other electricity storage technologies); and initial activity to consider a range of non-technology related factors (policy, regulation, economics, institutions etc.) likely to influence the adoption of energy storage.

CHINA

Support for the development and deployment of energy storage technologies in China is provided by a combination of national and regional/provincial government policy. At the national scale the Guiding Catalogue of Industrial Structure Adjustment (produced by the National Development and Reform Commission)[15] and aligned with China's 12th five-year plan, shapes Chinese industrial policy for the period 2011-15. Within this Catalogue, energy storage is identified as a Strategic Supporting Industry so enabling provincial governments to provide subsidies and support at a regional level.

A leading example of RD&D activity on energy storage, supported by a provincial government, is the collaboration between the Shanghai Municipal Government and China State Grid to deliver the Shanghai Smart Grid project. The objective of this project is to develop smart grid and associated energy storage RD&D capabilities within Shanghai, establishing a critical mass of expertise within a National Centre of Excellence. The energy storage RD&D activities, within this project, focus on the use and integration of battery technologies (including sodium sulphur, vanadium redox and lithium-ion) within a city-scale smart grid.

The shape and rate of development of China's domestic market for energy storage will be influenced by the abundance of wind resources and the recent rapid expansion of efforts to exploit these. A geographic mismatch exists between wind resource abundance and energy demand, creating a potential role for energy storage or other competing technologies (e.g. high-voltage direct current projects to strengthen the transmission network for long distance transfer) to enable integration of wind power into the grid.

15.The role of the National Development and Reform Commission is to formulate and implement economic and social development strategies.

EUROPEAN UNION

The EC Strategic Energy Technology Plan (SET-Plan) was the first step in developing and implementing a European energy technology policy (EC, 2009). The plan was initiated in 2007 with the aim to radically change the EC's approach to investment in RD&D activities targeted at achieving low carbon economy objectives. By outlining a vision (including non-binding targets for market performance, technology performance etc.) the SET-Plan establishes a framework within which joint public-private sector investment can rapidly accelerate the development and deployment of low carbon technologies. The SET-Plan presents roadmaps for a range of low carbon technologies, focussed on achieving 2020 low carbon economy objectives. Energy storage technologies sit within the scope of the electricity grids roadmap, and are closely aligned with the roadmaps for wind and solar technologies[16] (due to the potential role of energy storage in the integration of variable renewable resources).

The high-level roadmaps presented in the SET-Plan are complemented, and expanded upon, by a RD&D roadmap for materials enabling low carbon technologies (EC, 2011). This material roadmap proposes a research and innovation programme for the period 2012-2022, with the objective of supporting the development of a knowledge-based low carbon economy.

A roadmap for materials for electricity storage is included and addresses the major issue that adoption of energy storage technologies is currently hindered by technology costs and inadequate technical performance. The scope of the roadmap includes both research and industrial demonstration, and both energy orientated (batteries, CAES) and power orientated (supercapacitors, flywheels) storage technologies. Specific technical performance targets are presented for energy storage technologies (e.g. reducing the cost of lithium ion batteries to approx. €200/£167 per kWh), to be delivered by advances in the enabling materials (e.g. electrolytes and structural materials).

The relevant activities seeking to realise the vision presented in the SET-Plan are the Joint Programme on Energy Storage (focussing on strengthening capabilities for energy storage technology research) and the European Electricity Grid Initiative (focussing on system innovation and integration, and demonstration activities) (EEGI, 2010).

The Joint Programme on Energy Storage was launched in late 2011 and is managed by the European Energy Research Alliance. The objective of the programme is to accelerate the development of a range of energy storage technologies so they can be embedded within industry driven RD&D programmes (such as the European Electricity Grid Initiative outlined below). The Joint Programme will deliver detailed technology roadmaps under four technology themes – electrochemical storage, chemical storage, thermal storage, and superconducting magnetic energy storage – alongside work on a complementary techno-economic theme.

The objective of the European Electricity Grid Initiative is to enable delivery of the Smart Grid[17] vision (as outlined by the SET-Plan), over the period 2010-2030, by creating public-private partnerships to share the risk associated with the rapid development of electricity network technologies. Over the period 2010-18 the initiative will invest €60m (£50m) in energy storage RD&D projects, with a strong focus on addressing system integration issues. Links will be established to the research activities of the European Energy Research Alliance (such as the Joint Programme described above) and others, where further fundamental technology research is required.

16. Although the wind and solar technology roadmaps focus on competitors technologies for integration (such as HVDC), rather than energy storage technologies.

17. A user-centered, market-based, interactive, reliable, flexible, and sustainable electrical network system.

GERMANY

Energy storage is identified as playing a key role in the German Government's strategy for the transition to a reliable, economically viable and environmentally sound energy supply by 2050 (BMWI and BMU, 2011). The need to integrate renewable energy sources into the German grid is expected to drive the modernisation of the energy infrastructure, including a significantly expanded role for energy storage. Two key challenges for energy storage are identified: first, developing and promoting the adoption of energy storage technologies; and secondly, reshaping the market (in the context of increasing market liberalisation and competition) to enable the integration of energy storage technologies into the system. The German Government's energy strategy identifies the set of actions to support the expansion of national energy storage capacity, outlined below.

- **Immediate actions:** update legislation to approve energy storage systems for use in the control energy market and extend the grid charge exemption period for new storage plants (particularly pumped hydropower).
- **Short-term:** investigate appropriate incentives to encourage the adoption of biomass as a means of integrating intermittent renewables (e.g. wind and solar), pending the expansion of energy storage capacity in the medium to long-term (as outlined above).
- **Medium-term:** exploit, at all technological and economically feasible sites, pumped hydroelectric storage potential within Germany.
- **Long-term:** partner with other countries (e.g. Norway) to gain access to pumped hydroelectric storage capacity outside Germany.

In May 2011, three Federal Ministries – the Ministry of Economics and Technology, the Ministry for the Environment, Nature Conversion and Nuclear Safety and the Ministry of Education and Research – published a common call for proposals for research, development and demonstration (RD&D) of stationary energy storage technologies. A budget of €200m (£167m) has been allocated and the first group of projects have already started. Larger demonstration measures, such as wind-hydrogen plants or adiabatic air pressure storage systems, are in preparation and will be launched in spring 2012 (Höll, 2012).

RD&D activities to support the transition of energy storage technologies to market currently benefit from other substantial direct funding (€12.2m/£10.2m on electrical energy storage technology in 2010), and funding on related topics (€20.7m/£17.3m in funding was spent on fuel cell/hydrogen technologies, €16.8m/£14m on electric vehicles and €12.3m/£10.3m on smart grids in 2010) (BMU, 2011). To support the RD&D activities outlined above, the underpinning fundamental research required in materials and physical science has been identified as a priority area for investment within the Basic Energy Research 2020+ programme (BMBF 2011). Details of the support to be provided to energy storage related research under this programme are yet to be confirmed, but potential activities include development of strategic alliances between public and private sector actors to accelerate the transition of technologies to market.

Energy storage is one of three areas to be supported by a Government cross-department joint funding initiative (BMWI 2011) under the Federal Government 6th Energy Research Programme (2011-2014). The other two areas are electricity grids and energy efficient cities. These initiatives seek to ensure a coordinated approach to research, development and deployment, where whole-systems thinking is needed to address complexity and interdependencies and policy objectives require rapid transition of technologies from basic research to market. The energy storage joint funding initiative will focus on: making thermal storage technologies economically viable (to reduce energy demand within buildings, integrate solar thermal power and reduce requirements for electric storage capacity); and supporting the development of chemical (hydrogen and methane) and electrochemical storage technologies for mobile and stationary applications.

JAPAN

The Cool Earth Innovative Energy Technology Programme (METI, 2008a) identifies the set of 21 technologies that the Japanese Government will focus support on to deliver 50% reductions in greenhouse gas emissions by 2050 (against a 2007 baseline) and maintain/improve economic competitiveness. The set of technologies identified includes both high-performance power (electricity) storage and hydrogen storage, but does not include heat storage related technologies. The technology roadmap (METI, 2008b) for high-performance power (electricity) storage focuses on battery and capacitor technologies, as the existing strengths of Japanese industry and research in small scale energy storage (e.g. batteries for mobile devices) are perceived to provide a competitive advantage in emerging markets for larger scale battery storage applications (e.g. integration of variable renewables). The roadmap identifies a technology diffusion pathway where energy storage technologies develop to support the two applications.

- **Vehicles/mobile applications (pathway from 2010-50):** from public EVs and limited commuter EVs, via commuter EVs, to full specification EVs (i.e. specifications comparable to ICE vehicles).
- **Stationary applications (pathway from 2010-50):** from power quality improvement, via integration of solar and PV, to support for distributed generation.

For each application pathway the associated technology performance targets are identified, for example the targets for 2030 are: mobile applications – energy density 500 Wh/kg and Cost 5000 JPY/kWh (£42/kWh); and stationary applications – lifetime 20 years and 15000 JPY/kWh (£125/kWh).

Following the Great East Japan Earthquake and Fukushima nuclear power plant disaster (March 2011) the Government of Japan instigated two streams of activity to address immediate issues (Measures to Stabilise the Immediate Supply and Demand of Energy) and long-term issues (an Innovative Strategy for Energy and the Environment). An interim report on the approach to addressing long-term issues (Government of Japan, 2011) states that all energy and environment strategies (including the Strategic Energy Plan of Japan) will be reviewed in light of the Fukushima disaster. Whilst references to the role of energy storage in the interim report are limited, the direction of travel identified (reduction of dependency on nuclear power and bringing forward investments in distributed renewable sources) suggests a potential role for storage within the Japanese energy systems in the medium-term. Post-Fukushima supply issues have also stimulated interest in residential energy storage, to develop resilience at the individual household level to energy supply issues.

SOUTH KOREA

In May 2011 the South Korean Ministry of Knowledge Economy announced a $5.4bn (£3.4bn) investment in energy storage, with objective of becoming the global leader in the manufacture of energy storage systems. Approximately one third of the investment will be in R&D, with the remainder invested in demonstration projects and the development of energy storage infrastructure across South Korea. The development of the strategy for this major investment is likely to be informed by the outcomes of the Jeju Smartgrid Demonstration project (approx. $50m/£32m Government funding) where energy storage plays a critical role in enabling the integration of renewable energy sources into a city scale smart grid.[18]

18. http://www.smartgrid.or.kr/10eng3-1.php

UNITED STATES OF AMERICA

The US Department of Energy (Office of Electricity Delivery and Energy Reliability) has established an energy storage technologies programme (USDOE, 2011) with two objectives: improving the flexibility, economic efficiency, reliability and robustness of the US power grid; and delivering economic benefits through the transition of technologies to the commercial marketplace (estimated at approx. $2-4bn (£1.3–2.5bn) of benefits to the USA over a 20 year period (EPRI, 2011)). The delivery of the programme is led by the National Laboratories, in conjunction with universities and a range of industrial partners (small businesses, utilities, and manufacturers). Energy storage demonstration projects have also benefited from DOE support under the American Reinvestment and Recovery Act (2009).

The objective of the DOE program is to reduce the cost of energy storage by 30% by 2015, by investing $200m (£127m) (over the period 2011-2015) in the following areas:

- **research:** focused on chemical storage and battery technologies, with some investment in other areas;
- **demonstrations and deployments at commercial scale:** across the range of energy storage technologies (including batteries, flywheels, CAES etc.);
- **systems analysis:** focused on effectively integrating energy storage technologies within the grid.

For each of these areas near-term objectives[19] (to be achieved within five years) and longer-term objectives[20] have been set, with milestones identified on the pathway to the near-term objectives. The milestones identified (exemplars listed below) show that complementing the core focus on technology development, the scope of the programme also includes developing understanding of the role of markets and institutions in the adoption of energy storage technologies; and the emerging business opportunities associated with energy storage.

- Develop and demonstrate 5 kW sodium beta-alumina battery prototype system capable of satisfactory operation <250°C.
- Award $2.8m (£1.6m) in university contracts for Applied Energy Storage Research.
- Report on institutional barriers for wide-scale market adoption of stationary energy storage.
- Publish report on the value of energy storage to the utility grid directed at regulatory and legislative audiences.
- Report on market design to support adoption of storage.

State government activities are also playing a prominent role, complementing the activities of the National Government (such as the DOE Energy Storage Program described above), in facilitating the transition of energy storage technology to market. For example, the California Energy Commission has engaged in a strategic analysis of energy storage technologies that could be feasible for implementation at scale by 2020 (Abele et al, 2011):

- identifying the California State target for 33% of electricity to be generated from renewable sources by 2020, as creating the need for a larger, more effective energy storage capability within the grid (to enable integration of renewable sources);
- providing a summary for a range of energy storage technologies (including CAES, battery technologies and hydrogen) of current technology status (i.e. technology readiness level), limitations and emerging opportunities;
- mapping the policy instruments that impact upon the deployment of energy storage technologies within California;
- identifying technology gaps, research needs and policy reforms to be addressed by regulatory organisations (including the California Energy Commission itself and the California Public Utilities Commission) in supporting the transition of energy storage technologies to market.

19. e.g. develop battery technologies to meet the following targets: system capital costs under $250/kWh (£158/kWh); system efficiency over 75%; cycle life more than 4000 cycles.

20. e.g. develop battery technologies to meet the following targets: system capital costs under $150/kWh (£95/kWh); system efficiency over 80%; cycle life more than 5000 cycles.

IRELAND

The Irish Government White Paper on Energy (DCENR, 2007) outlines the policy framework for 2007-2020, and identifies RD&D for energy storage technologies as a priority area for government support. The ambitious targets set for renewable sources – 50% of supply by 2025 (SEAI, 2010) – and the nature of the Ireland's energy infrastructure, relatively small in scale and with limited interconnection, are expected to create a significant role for energy storage technologies. Particular interest has been evident in the potential of energy storage to enable intermittent wind resources in to the Ireland grid (Gonzalez et al, 2004), with this interest emerging relatively early (2004) compared to other countries discussed in this section. Whilst there is no current roadmap for energy storage, it plays a prominent role within the smart grid roadmap for Ireland (SEAI, 2011). This roadmap envisions how an Irish smart grid can be delivered by 2050, with electrification of thermal energy supply expected to minimise the role of thermal storage, and pilot deployments of electricity storage systems expected to take place from 2020-2035.

DENMARK

Danish energy policy (Danish Government, 2011a) identifies establishing energy and transport systems based 100% on renewable energy by 2050 as the primary government objective. On the pathway to achieving this overarching objective, milestones are identified – demonstrating a focus on exploiting wind power resources (50% of electricity demand to be meet by wind by 2020), and electrification to enable heat demand to be met from renewable supplies (electricity and heat supply to be covered by renewable energy by 2035). Energy storage is a central component of the vision of the 2050 Danish energy system (Danish Government 2011b) with a range of possible approaches (including those listed below) considered worthy of further exploration, whilst the current Danish smart grid strategy remains energy storage technology agnostic (Energinet.dk and DEA, 2011).

- Using the Danish natural gas infrastructure to store excess energy from wind turbine installations (Energinet.dk et al, 2011), it is envisioned that excess electricity would be used to generate hydrogen gas, which could then be stored, distributed and used as a fuel for electricity generation, as and when required.
- Developing the relationships and infrastructure to enable access to pumped hydropower energy storage capacity in Norway and Sweden.
- Using large-scale heat storage installations within district heating systems to store heat converted from excess electricity by heat pumps (Danish Commission on Climate Change Policy (2010).

8: CONCLUSIONS AND RECOMMENDATIONS

The storage of electricity and heat has the potential to play a much more significant role in matching supply and demand in a future decarbonised UK energy system than has been the case while fossil-fuels dominated. However, assessing the optimal future pathway for the deployment of energy storage is complex, due to the different technologies and possible applications involved and because of the many drivers and barriers that will have an impact.

Most of the existing analysis for the UK and other countries has examined the role of electrical storage in large-scale grid applications. However, there is emerging evidence to suggest that decentralised energy storage, including thermal applications, may also offer significant benefits to the UK energy system. This report has examined some of the most important factors that will impact on the deployment of energy storage and examined their potential interactions through a number of illustrative pathways. Key conclusions from this analysis are as follows:

- Increased electricity generation from variable renewable sources, such as wind, combined with the electrification of heat in homes are two of the most important factors likely to drive the deployment of energy storage. Other energy system characteristics that will impact on energy storage (either positively or negatively) include the penetration of plug-in hybrid and all-electric cars; the availability of cheap and flexible fossil-fuel generation; the extent of CHP and district heating; the demand for space cooling; the extent of electricity interconnection with other countries; and the degree of demand-side response.
- There are many different technologies for heat or electrical storage at different stages of maturity and with a wide range of characteristics. It is unlikely that a single solution will emerge in the future given the wide variations in possible applications. Pumped storage and compressed air energy storage are both commercial technologies for long-term large-scale storage and may be joined by flow batteries, hydrogen and cryogenic energy storage in the longer term. For fast response, flywheels are currently commercial, but supercapacitors also offer interesting prospects. In decentralised applications, a wide variety of battery technologies are relevant, with lead-acid and nickel and sodium-sulphur the most likely near term choices, and metal-air holding longer-term promise. The use of second-life lithium-ion batteries could be an interesting option. A variety of heat storage technologies, including those using novel materials, are also worth investigating further.

- Energy storage currently faces a number of regulatory and market barriers. While a number of studies have shown that storage can bring benefits across the electricity system, it may be too expensive for any discrete part of the value chain to realise a sufficient return on investment. In addition, the regulatory arrangements in the UK separate monopoly and competitive activities, and so network companies – distribution and transmission – cannot own energy storage facilities and use them in the trading environment. Finally, storage often has the greatest value to the system when placed closest to the source of demand, but current regulatory and business models are unlikely to allow this opportunity to be exploited fully.
- Public attitudes towards energy storage could be crucial in determining its role in the energy system, but to date little or no work has been undertaken in this area. While macro-scale storage is likely to be viewed in a similar way to other industrial installations, micro-storage will probably need to satisfy many of the criteria that are normally associated with consumer devices. Affordability, controllability, performance, aesthetics and fit with the domestic or work habits will therefore all be important. Without a strong incentive to install, evidence from other technologies suggests that uptake is likely to be low to modest.
- The UK is not alone in showing a renewed interest in energy storage. Many other countries including China, Japan, the United States and several in Europe all have substantial energy storage activities. While the focus has largely been on technology research, development and demonstration (particularly for batteries) there is now some initial activity to consider a range of non-technology related factors likely to influence the adoption of energy storage.

The overarching message from this report, as illustrated by the pathways, is the need to assess the role of energy storage through an integrated systems approach that takes account of all relevant factors that can impact its deployment. Areas for further research within such an integrated framework should include:

- analysing both electricity and heat storage technologies across all scales and across all applications, including centralised, decentralised and demand-side markets;
- technology-based systems modelling that combines the necessary temporal granularity to accurately represent storage, and the ability to model the wider energy system, to clearly identify the potential contribution of energy storage in a low-carbon energy system under a range of scenarios to 2050;
- identifying UK priorities for research, development and demonstration relating to energy storage, taking account of existing expertise and likely domestic and export opportunities;
- examining reforms to the current regulatory and market structures that can address market failures, and investigating whether any more targeted forms of support would be justified to remove barriers to the deployment of both electricity and heat storage;
- investigating potential business models that could support the deployment of storage;
- undertaking new empirical research on public attitudes to energy storage;
- highlighting areas where international collaboration on energy storage could add value to UK activities.

One way of bringing these elements together would be for relevant stakeholders, including government, researchers, business, regulators and representatives from civil society to join forces to develop a roadmap for the deployment of energy storage in the UK.

This should draw on the results of the above activities to identify the near-term actions for all relevant stakeholders that are necessary to take forward the roadmap's recommendations.

GLOSSARY

Air source heat pump
A heating and cooling system that uses outside air as a heat source to warm buildings.

All-electric vehicle (EV)
A vehicle that is powered entirely by electricity from an on-board battery.

Back-up generation capacity
Generation capacity that is held in reserve and only operated to cover a shortfall in electricity supply, due to a power station breakdown or other unexpected event.

Carbon budget
A set amount of carbon that can be emitted in a given amount of time, either by a country or by a particular set of activities.

Carbon capture and storage (CCS)
A technology to reduce the release of CO_2 emissions from large point sources, such as fossil fuel power plants, by capturing the gas and permanently storing it away from the atmosphere.

Combined heat and power (CHP)
A plant designed to produce both heat and electricity from a single heat source.

Distribution network operator (DNO)
A company holding a licence to distribute electricity to customers in a particular region.

Distribution System Operator (DSO)
A DNO that actively manages generation and loads connected to its network.

District heating (DH)
The supply of heat from a centralised source to customers via a network of distribution pipes.

Electricity Market Reform (EMR)
A set of UK Government proposals to stimulate large scale investment in low carbon generation.

Feed-in Tariff (FIT)
A subsidy scheme which rewards small scale renewable generation at a fixed rate per kWh.

Flexible demand
Demand for electricity or energy that can be shifted in time or reduced e.g. in response to a change in price.

Green Deal
A UK Government CO_2 emission reduction policy that provides financing for energy efficiency investments in businesses and households.

Ground source heat pump
A heating and cooling system that pumps heat from the ground to warm buildings (or vice-versa).

Hydroelectric power
Generating electricity by conversion of the energy of running water.

Internal combustion engine (ICE) vehicles
A vehicle powered by an engine whose fuel (usually petrol or diesel) is burned inside the engine itself rather than in an outside burner.

Interconnector
An electricity transmission line linking two countries.

Low Carbon Networks (LCN) Fund
A fund established by Ofgem to support projects sponsored by the distribution network operators to trial new technology, operating and commercial arrangements.

MARKAL
A generic modelling framework that can be tailored by the input data to represent the evolution over time of a specific energy system at the national, regional, or community level.

National Grid
The UK electricity and gas system operator. National Grid also holds the licence to operate the transmission network in England and Wales.

Off-peak demand
A period when energy or electricity demand is low.

Offshore wind
Generating electricity by conversion of energy from the wind using turbines located at sea.

Ofgem
The energy regulator in Great Britain.

Onshore wind
Generating electricity by conversion of energy from the wind using turbines located on land.

Peak demand
A period of strong energy or electricity demand.

Plug-in hybrid vehicles (PHEV)
A hybrid vehicle with both a conventional internal combustion engine and an electric motor, which uses rechargeable batteries and can be fully charged by connecting a plug to an external electric power source.

Renewable Heat Incentive
A UK Government-backed financial support scheme to support a range of renewable energy technologies for generating heat.

Second-life batteries
The use of old batteries (e.g. from electric cars) for a different purpose.

Solar photovoltaic (PV) power
Generating electricity by conversion of the energy in sunlight.

Space cooling
Conditioning of room air for human comfort by a refrigeration unit or by the circulation of chilled water through a central- or district-cooling system.

System operator (SO)
A body which oversees and manages the flow of electricity across the transmission network.

Thermal power generation
A power plant in which electricity is generated from heat.

Tidal power
Generating electricity by conversion of the energy in ocean tides.

Transmission network operator (TNO)
A company holding the licence to operate a transmission network in a particular region.

Vehicle-to-grid (V2G) technology
A system in which plug-in electric vehicles, such as electric cars and plug-in hybrids, link with the power grid by either delivering electricity into the grid or by adjusting their charging rate.

Wave power
Generating electricity by conversion of the energy in ocean waves.

REFERENCES

Abele, A. et al. (2011)
2020 Strategic Analysis of Energy Storage in California, California Energy Commission. www.energy.ca.gov/publications/displayOneReport.php?pubNum=CEC-500-2011-047.

BMBF (2011)
Basic Energy Research 2020+ - The Funding of Energy Research by the Federal Ministry of Education and Research, Federal Ministry of Education and Research. www.research-in-germany.de/main/research-areas/energy/e2-1-programmes-initiatives/46944/e3-5-basic-energy-research-2020-.html.

BMU (2011)
Innovation Through Research – 2010 Annual Report on Research Funding in the Renewable Energies Sector, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. www.bmu.de/english/publication/content/35028.php#Energy.

BMWI (2011)
Research for an environmentally sound, reliable and affordable energy supply (6th Energy Research Programme of the Federal Government), Federal Ministry of Economics and Technology, November 2011.

BMWI and BMU (2011)
The Federal Government's energy concept of 2010 and the transformation of the energy system of 2011, Federal Ministry of Economics and Technology and Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. www.bmu.de/files/english/pdf/application/pdf/energiekonzept_bundesregierung_en.pdf.

Bolton, R. and T. Foxon (2011)
Governing Infrastructure Networks for a Low Carbon Economy: Co-Evolution of Technologies and Institutions in UK Electricity Distribution Networks, Competition and Regulation in Network Industries, 12(1), 2-26.

BRE (2007)
Energy use in homes, www.bre.co.uk/page.jsp?id=1753.

CLG (2009)
English House Condition Survey 2007, Department for Communities and Local Government, London. www.communities.gov.uk/documents/statistics/pdf/1133548.pdf.

Danish Commission on Climate Change Policy (2010)
Green energy – the road to a Danish energy system without fossil fuels. www.ens.dk/en-US/policy/danish-climate-and-energy-policy/danishclimatecommission/greenenergy/Documents/green%20energy%20GB%20screen%201page%20v2.pdf.

Danish Government (2011a)
Our Energy Future. www.ens.dk/Documents/Netboghandel%20-%20publikationer/2011/our_future_energy_%20web.pdf.

Danish Government (2011b)
Energy Strategy 2050 – from coal, oil and gas to green energy. www.ens.dk/en-US/policy/danish-climate-and-energy-policy/danishclimatecommission/aboutthecommission/Documents/Energy%20Strategy%202050%20web.pdf.

DECC (2011a)
The Carbon Plan: Delivering our low carbon future, Department of Energy and Climate Change. http://www.decc.gov.uk/en/content/cms/tackling/carbon_plan/carbon_plan.aspx.

DECC (2011b)
Planning our electric future: a White Paper for secure, affordable and low-carbon electricity, Department of Energy and Climate Change. www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/emr_wp_2011.aspx.

DECC (2011c)
Planning our electric future: technical update, Department of Energy and Climate Change. www.decc.gov.uk/en/content/cms/legislation/white_papers/emr_wp_2011/tech_update/tech_update.aspx.

DCENR (2007)
Delivering a Sustainable Energy Future for Ireland, Department of Communications, Energy and Natural Resources. www.dcenr.gov.ie/Energy/Energy+Planning+Division/Energy+White+Paper.htm.

EA Technology (2010)
Operating the Electricity Transmission Networks in 2020, EA Technology's submission to National Grid's Consultation. www.nationalgrid.com/NR/rdonlyres/1AC22FC4-4B5D-4D89-93E5-0E09B1CD456E/38392/EATechnology.pdf.

EC (2009)
Commission staff working document accompanying document to the communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on Investing in the Development of Low Carbon Technologies (SET-Plan). A technology roadmap, SEC(2009) 1295, Brussels. http://setis.ec.europa.eu/about-setis/technology-roadmap/Complete%20report.pdf/view.

EC (2011)
Materials Roadmap Enabling Low Carbon Energy Technologies, European Commission, Brussels. http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view.

EGGI (2010)
The European Electricity Grid Initiative (EEGI) Roadmap 2010-18 and Detailed Implementation Plan 2010-12. http://setis.ec.europa.eu/activities/implementation-plans/Grid_EII_Implementation_plan_final.pdf/view.

Eneginet.dk and Danish Energy Association (2011)
Smart grid in Denmark. www.energinet.dk/EN/FORSKNING/Energinet-dks-forskning-og-udvikling/Smart-Grid/Sider/default.aspx.

Energinet.dk et al (2011)
Energy 2011 – Annual report on Danish energy research programme. http://en.fi.dk/publications/2011/energy2011/?searchterm=energy.

EPRI (2010)
Electricity Energy Storage Technology Options. A White Paper Primer on Applications, Costs, and Benefits, Electric Power Research Institute, Palo Alto, CA. www.electricitystorage.org/images/uploads/static_content/technology/resources/ESA_TR_5_11_EPRIStorageReport_Rastler.pdf.

EPRI (2011)
Estimating the Costs and Benefits of the Smart Grid: A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid, Electric Power Research Institute, Palo Alto, CA. http://my.epri.com/portal/server.pt?Abstract_id=000000000001022519.

ERP (2011)
The future role for energy storage in the UK, Main Report, Energy Research Partnership, June 2011. www.energyresearchpartnership.org.uk/energystorage.

Foxon, TJ (2011)
A coevolutionary framework for analysing a transition to a sustainable low carbon economy, Ecological Economics, 70, 2258-2267.

Foxon, T.J. and P.J. Pearson (2011)
Transition pathways for a UK low carbon electricity system: exploring roles of actors, governance and branching points, Working Paper for 2nd International Conference on Sustainability Transitions: "Diversity, Plurality and Change: Breaking New Grounds in Sustainability Transitions Research", University of Lund, Lund, Sweden, 13-15 June 2011.

Gonzalez, A. et al. (2004)
Study of Electricity Storage Technologies and Their Potential to Address Wind Energy Intermittency in Ireland. http://www.seai.ie/Renewables/Smart_Grids/The_Smart_Grid_for_the_Consumer/Business_Consumer/Embedded_Energy_Storage/.

Government of Japan (2011)
Interim Compilation of Discussion Points for the Formulation of "Innovative Strategy for Energy and the Environment", The Energy and Environment Council (Government of Japan). www.npu.go.jp/en/policy/policy06/index.html#p2.

Great Britain. Climate Change Act 2008, London, The Stationery Office. www.legislation.gov.uk/ukpga/2008/27/contents.

Gross, R. et al. (2006)
The Costs and Impacts of Intermittency, UK Energy Research Centre, London. www.ukerc.ac.uk/Downloads/PDF/06/0604Intermittency/0604IntermittencyReport.pdf.

Grünewald, P. et al (2011)
The role of large scale storage in a GB low carbon energy future: Issues and policy challenges, Energy Policy, 39, 4807–4815.

Hauer, A. (2011)
Storage Technology Issues and Opportunities, presentation to the IEA Committee on Energy Research and Technology Energy Storage Workshop, 15 February 2011, Paris. www.iea.org/work/2011/storage/Item1_ECES.pdf.

Höll, A (2012)
Personal Communication, 9 February 2012.

Imperial College (2012)
Workshop on the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future, 11 January 2012, Imperial College.

Lottner, V. and D. Mangold (2000)
Status of seasonal thermal energy storage in Germany, Terrastock, Stuttgart, Germany, 28 August – 1 September 2000. www.itw.uni-stuttgart.de/abteilungen/rationelleEnergie/pdfdateien/00-08.pdf.

Meeus, l., Purchala, K., van Hertem, D. & Belmans, R. (2006)
Regulated cross-border transmission investment in Europe. European Transactions on Electrical Power, 16, 591-601.

METI (2008a)
Cool Earth – Innovative Energy Technology Program, Ministry of Economy, Trade and Industry (Japan). www.meti.go.jp/english/newtopics/data/pdf/031320CoolEarth.pdf.

METI (2008b)
Cool Earth – Innovative Energy Technology Program (Technology Development Roadmap), Ministry of Economy, Trade and Industry (Japan). www.meti.go.jp/english/newtopics/data/pdf/CE_RoadMap.pdf.

National Grid (2009)
Operating the Electricity Transmission Networks in 2020: Initial Consultation. www.nationalgrid.com/NR/rdonlyres/32879A26-D6F2-4D82-9441-40FB2B0E2E0C/39517/Operatingin2020Consulation1.pdf.

National Grid (2011a)
2011 National Electricity Transmission System (NETS) Seven Year Statement. www.nationalgrid.com/uk/Electricity/SYS/.

National Grid (2011b)
Operating the Electricity Transmission Networks in 2020 - Update June 2011, https://www.nationalgrid.com/NR/rdonlyres/DF928C19-9210-4629-AB78-BBAA7AD8B89D/47178/Operatingin2020_finalversion0806_final.pdf.

NERA and AEA Technology (2010)
Decarbonising heat: low-carbon heat scenarios for the 2020s. Report to the Committee on Climate Change. http://downloads.theccc.org.uk.s3.amazonaws.com/4th%20Budget/fourthbudget_supporting_research_NERA-AEA_Decarbonising_heat.pdf.

Ofgem (2011)
Promoting smarter energy markets, http://www.ofgem.gov.uk/Markets/sm/strategy/Pages/Strategy.aspx.

Pöyry (2011)
The challenges of intermittency in North West European power markets. www.poyry.com/linked/en/press/NEWSIS.pdf.

Schallenberg, R. H. (1981)
The Anomalous Storage Battery: An American Lag in Early Electrical Engineering, Technology and Culture, 22, 725-752.

SEAI (2010)
Strategic Plan 2010-2015, Sustainable Energy Authority of Ireland. http://www.seai.ie/Publications/SEAI_Publications/.

SEAI (2011)
Smart Grid Roadmap, Sustainable Energy Authority of Ireland. www.seai.ie/Publications/SEAI_Roadmaps/Smartgrid_Roadmap.pdf.

Speirs J. et al (2010)
Building a roadmap for heat: 2050 scenarios and heat delivery in the UK, a report to the Combined Heat and Power Association. www.chpa.co.uk/medialibrary/2011/04/07/e9a9f61d/Building_a_roadmap_for_heat_Full.pdf.

Strbac G. et al (2010)
Benefits of advanced smart metering for demand response based on control of distribution networks: Summary report. www.cts.cv.ic.ac.uk/documents/publications/iccts01392.pdf.

Royal Academy of Engineering (2012)
Heat: degrees of comfort? Options for heating homes in a low carbon economy. www.raeng.org.uk/news/publications/list/reports/RAE_Heat_Booklet.pdf.

Rhodes, A. (2012)
Low carbon heat: commercial opportunities and challenges for the UK, Energy Generation and Supply Knowledge Transfer Networks. https://connect.innovateuk.org/web/low-carbon-heat.

UKERC (2011)
The future of energy storage: stakeholder perspectives and policy implications. UK Energy Research Centre, May 2011. www.ukerc.ac.uk/support/tiki-index.php?page_ref_id=2889.

Upham, P., Whitmarsh, L., Poortinga, W., Purdam, K. and Devine-Wright, P. (2009)
Public Attitudes to Environmental Change – a selective review of theory and practice, report for RCUK/LWEC, http://www.lwec.org.uk/news-archive/2009/30102009-report-published-public-attitudes-environmental-change.

USDOE (2011)
Energy Storage - Program Planning Document, US Department of Energy, Office of Electricity Delivery & Energy Reliability. http://energy.gov/node/238771.

Whitmarsh, L, Upham, P., Poortinga, W., McLachlan, C., Darnton, A., Devine-Wright, P., Demski, C. and Sherry-Brennan, F. (2011)
Public Attitudes to and Engagement with Low-Carbon Energy: A selective review of academic and non-academic literatures. Report for RCUK Energy Programme, http://www.rcukenergy.org.uk/news.html.

Wilson, I.A.G. et al (2010)
Energy storage in the UK electrical network: estimation of scale and review of technology options, Energy Policy, 38, 4099-4106.

CONTACTS

Centre for Low Carbon Futures

Director: Jon Price

jon.price@lowcarbonfutures.org

Centre for Low Carbon Futures

IT Centre

York Science Park

York YO10 5DG

Telephone: +44 (0)1904 567714

www.lowcarbonfutures.org

Twitter: @clcfprojects

ACKNOWLEDGMENTS

This report has benefited from discussions and inputs involving a large number of people, including participants in a workshop held in Leeds on 17 January 2012.

In particular, the authors would like to thank the following: Dave Anelli, Eon; Nigel Brandon, Imperial College; Alastair Buckley, University of Sheffield; Brian Collins, Former Chief Scientific Adviser in BIS and DfT; Jenny Cooper, National Grid; Matthew Cotton, University of Leeds; Yulong Ding, University of Leeds; Craig Dyke, National Grid; Martin Foster, University of Sheffield; Tim Foxon, University of Leeds; Andy Gouldson, University of Leeds; Philipp Grünewald, Imperial College; Peter Hall, University of Sheffield; John Harris, UK Coal Forum; Andrew Haslett, Energy Technologies Institute; Tom Knowland, Leeds City Council; Matthieu Lasfargues, University of Leeds; John Loughhead, UK Energy Research Centre; Nafees Meah, Department for Energy and Climate Change; Elizabeth Milson, Department for Energy and Climate Change; Mohamed Pourkashanian, University of Leeds; Anthony Price, Swanbarton, Ltd; Huw Price, University of Sheffield; Jon Price, Centre for Low Carbon Futures; Jonathan Radcliffe, Energy Research Partnership; Anthony Rennie, University of Sheffield; Steve Saunders, Arup; Jason Stoyel, CO_2Sense; James Sun, The Carbon Trust; Melanie Taylor, Leeds City Council; Diego Villalobos, Ofgem; David Vincent, David Vincent and Associates; Phillip Webber, University of Leeds; Richard Williams, University of Birmingham; Grant Wilson, University of Sheffield; and Nick Winser, National Grid.

The authors would also like to acknowledge the support of Gill Holt, Katherine Robinson and Sarah Schepers from the Centre for Low Carbon Futures.

ABOUT US

The Centre for Low Carbon Futures is a collaborative membership organisation that focuses on sustainability for competitive advantage. Founded by the Universities of Hull, Leeds, Sheffield and York, the Centre brings together multidisciplinary and evidence-based research to both inform policy making and to demonstrate low carbon innovations. Our research themes are Smart Infrastructure, Energy Systems and the Circular Economy. Our activities are focused on the needs of business in both the demonstration of innovation and the associated skills development. Registered in the UK at Companies House 29th September 2009 Company No: 7033134.

CLCF is grateful for funding and support from Accenture, the Beijing Institute of Technology, British Deputy High Commission of India, British Embassy Tokyo, China Beijing Environmental Exchange (CBEEx), Committee on Climate Change of the UK, the Energy Intensive Users Group, ICLEI- Local Governments for Sustainability (Tokyo), Indian Chamber of Commerce, International Institute for Sustainable Development (IISD), Jadavpur University, the Regional Development Agency, the Trades Union Congress, the UK Department of Energy and Climate Change, Tecnológico de Monterrey Mexico City, the University of Birmingham, the University of Hull, the University of Leeds, the University of Sheffield and the University of York.