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Developing pathways for energy storage in the UK using a coevolutionary framework

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Abstract

A number of recent techno-economic studies have shown that energy storage could offer significant benefits to a low-carbon UK energy system as it faces increased challenges in matching supply and demand. However, the majority of this work has not investigated the real-world issues affecting the widespread deployment of storage. This paper is designed to address this gap by drawing on the systems innovation and socio-technical transitions literature to identify some of the most important contextual factors which are likely to influence storage deployment. Specifically it uses a coevolutionary framework to examine how changes in ecosystems, user practices, business strategies, institutions and technologies are creating a new selection environment and potentially opening up the energy system to new variations of storage for both electricity and heat. The analysis shows how these different dimensions of the energy regime can coevolve in mutually reinforcing ways to create alternative pathways for the energy system which in turn have different flexibility requirements and imply different roles for storage technologies. Using this framework three pathways are developed – user led, decentralised and centralised - which illustrate potential long-term trajectories for energy storage technologies in a low-carbon energy system.

Keywords
Energy storage
Socio-technical transitions
Low-carbon energy system

1. Introduction

The United Kingdom (UK) has committed to reduce its greenhouse gas emissions so that, by 2050, emissions are at least 80% below 1990 levels (Great Britain, 2008). This goal will require significant changes to the way in which energy is produced and used - including a huge increase in the use of renewable energy, a substantial rise in the demand for electricity to provide heat and transport and sustained improvements in energy efficiency (HM Government, 2011). Such developments are likely to pose significant challenges for the energy system in matching supply and demand, and so could create substantial opportunities for the deployment of additional electricity and heat storage. For instance, a recent assessment by the Low Carbon Innovation Coordination Group examined the value of innovation in energy storage to decarbonising the UK energy system. It concluded that the deployment of energy storage technologies has the potential to yield total system cost savings of between £2-10 billion over the period to 2050, while creating a market worth between £3 bn and £26 bn over the same period (Low Carbon Innovation Coordination Group, 2012).

Currently, most of the energy storage capacity in the UK energy system is provided by stocks of fossil fuels. Wilson, McGregor et al. (2010) estimated the electricity that could be generated from UK stocks of coal and gas destined for the power sector was around 30 000 GWh and 7 000 GWh respectively. In contrast, electricity and heat storage is several orders of magnitude lower. Bulk electricity storage - provided by pumped hydroelectric plants – totals only 28 GWh. There are also a few smaller electricity storage facilities connected to the distribution system, most of which are demonstration projects involving various types of battery. Heat storage is largely distributed and mostly at an individual building scale and is either provided by hot water cylinders (installed in around 14 million homes, giving a maximum storage capacity of around 80 GWh) or by electrical storage heaters (which are the main source of heating in 1.6 million dwellings). A number of district heating schemes in the UK also have hot water storage associated with them.

Despite the likely challenges in matching supply and demand in a low-carbon future, storage has not been well represented in the majority of future scenarios for the UK energy system (ERP, 2011). As a result, there has been little detailed analysis of the potential role of energy storage in helping the UK to achieve deep emission reductions or investigation of the range of factors that could impact its deployment prospects. To the extent that current scenarios consider energy storage at all, they largely focus on the role of bulk, centralised electricity storage, such as pumped hydro-electric storage – with little, if any, consideration for heat storage (Committee on Climate Change, 2008; HM Government, 2011).

Until recently, most energy storage research has focused on developing a range of technologies with different characteristics (Baker, 2008; Chen et al., 2009; Hall and Bain, 2008), rather than examining how different storage technologies might operate in a low-carbon context and their value or means of integration into energy systems. In the case of the UK energy system, notable exceptions include an early techno-economic analysis by UMIST for the Department of Trade and Industry (DTI, 2004) and more recent work on the role of storage by Grünewald et al. (2011) and Wilson et al. (2011). One of the few studies to look at the broader regulatory and policy issues is (ERP, 2011).

However, over the last year there has been a growing interest in the role that energy storage could play in a low-carbon energy system. A recent major techno-economic analysis commissioned by the

Carbon Trust (Strbac et al., 2012b) concluded that energy storage technologies could have significant value to a low-carbon UK energy system, particularly one with a large contribution of renewable generation. Furthermore it found that distributed storage could offer higher value to the electricity system than bulk storage, due to distribution network savings.

However, energy storage is not the only solution to meeting the challenges posed by a low-carbon energy system. Back-up fossil generation capacity, interconnectors and flexible demand, amongst others, can also play a role. The competition and interaction between these alternative balancing technologies has been explored in a recent report (Strbac et al., 2012a) for the Department of Energy and Climate Change (DECC). This study found that the efficient amount of distributed storage is highly sensitive to its cost and the level of demand side response in the system; on the other hand it is not sensitive to the level of interconnection and flexible generation.

These recent modelling analyses take a ‘whole systems’ perspective and assume a perfectly competitive electricity market. They therefore do not take into account many of the real-world issues which affect storage deployment, such as the structure of electricity markets and regulations and the interaction of users with domestic scale storage applications. Some of these issues are explored by Grünewald et al. (2012) through combining stakeholder interviews and socio-technical transitions theory. They find that distributed electricity storage currently faces a number of challenges associated with technology lock-in and path dependency resulting from poor alignment of the current regulatory regimes governing generation, networks and consumption with the requirements for storage.

Our paper builds on, and extends, the arguments presented by Grünewald et al. (2012) by bringing a comprehensive whole systems understanding of the factors that impact energy storage, including the role of technology, institutions, business practices and users. This is achieved by using a coevolutionary framework (Foxon, 2011) to integrate these different dimensions into a number of long-term pathways for both electricity and heat storage, so identifying future opportunities and challenges for this group of technologies. In Section 2 we outline this framework, which is based on insights from the innovation studies and socio-technical transitions literatures, and explain how we have applied it to examine energy storage in the UK. Section 3 then reviews the key contextual factors that are likely to influence storage deployment in the transition to a low-carbon energy system, drawing on the output of a workshop which included key industry stakeholders, academics and policy-makers. Following this, Section 4 presents our illustrative pathways for energy storage in the UK, which are based on different forms of coevolutionary interaction between technology, institutions, business practices and users. Section 5 then analyses the energy storage pathways in more detail, highlighting potential risks that may lead to ‘branching points’ (Foxon et al., 2013) along the pathways. Finally, in Section 6 we present our conclusions, including some implications of our findings for policy.

2. Analytical framework and methods

In this section we draw from the extensive literature on system innovation and socio-technical transitions to frame and analyse prospective energy storage pathways. A key motivation in doing so was to move beyond much of the existing analysis which tends to treat storage as individual technologies with little consideration of how different applications might operate in a wider energy system context, and to try to capture the wider social and institutional factors which might influence storage in a low-carbon energy future.

2.1 A systems perspective on energy storage deployment

Innovation processes in large scale systems such as energy supply have a different character than conventional product based sectors. The complex and interconnected nature of infrastructure and its public good character means that a wide range of actors and institutions - including government, regulators, and lobby groups - influence technical change in these sectors. In our analysis of energy storage innovation and deployment we must therefore look beyond the traditional producer-user relationships. While cost and performance of technologies are of course important, the institutional environment, governance structures and the willingness of users to engage with new technologies will be a key factor in influencing which innovations emerge and the degree to which they are deployed across a system.

Recognising this, recent studies which adopt a socio-technical transitions perspective have emphasised that the diffusion of individual technologies, such as energy storage, cannot be considered in isolation, but rather occur in the context of a wider system or regime (Foxon et al., 2005; Verbong and Geels, 2007). Regimes are composed of '(networks of) actors (individuals, firms, and other organisations, collective actors) and institutions (societal and technical norms, regulations, standards of good practice) as well as material artefacts and knowledge' (Markard et al., 2012: p.956) and provide structure and stability to large scale and complex socio-technical systems. Transitions theory argues that regimes act as strong selection environments for a variety of technologies and practices, those which align well are likely to be adopted whereas technologies and practices which do not are likely to be confined to niche applications. (Geels, 2002, 2004; Raven, 2005).

The initial stages of regime formation will likely have a great bearing on the subsequent processes of technical change. Unruh (2000) argues that dominant designs, such as centralised electricity storage, emerge following a period of variation when many competing technologies operate in the market. Typically, during this 'era of ferment', significant cost and performance improvements are achieved as technologies vie for market position; the outcome of innovation processes is therefore highly uncertain. In early urban electricity systems, for example, a number of small scale battery applications were deployed in an effort to improve the load factor of small scale urban direct current (DC) systems (Hughes, 1983; Schallenberg, 1981). However, innovations in long distance transmission technology followed and centralised pumped hydro-electric storage emerged as the dominant design.

The transitions and innovation systems literature argues that over time incumbent regimes benefit from increasing returns to scale and adaptation, along with positive learning effects (Arthur, 1989; Arthur, 1994; Foxon, 2003; Unruh, 2000). For the case of infrastructure based technologies there is also a strong network effect as technologies that fit in with the overall system architecture are likely to benefit. Pumped storage, for example, benefited in the emerging centralised regime structure, partly because it operates at the same scale as centralised generation. This points to the fact that storage deployment is particularly dependent on developments in the wider energy system (Grünewald et al., 2012). As such, it can be regarded as a system-dependent technology, which unlike innovation in power generation or demand-side practices, will not be the motive force behind an energy transition, but can enable or constrain alternative low-carbon transition pathways. As regimes develop, there is a risk that 'apparently inferior designs can become locked-in through a path-dependent process in which timing, strategy and historic circumstance, as much as optimality, determine the winner' (Unruh, 2000: p. 820). This raises the potential that energy storage technologies which could help to reduce the overall system costs of the low-carbon transition over the longer-term may become locked-out as they are not commercially viable under current market arrangements.

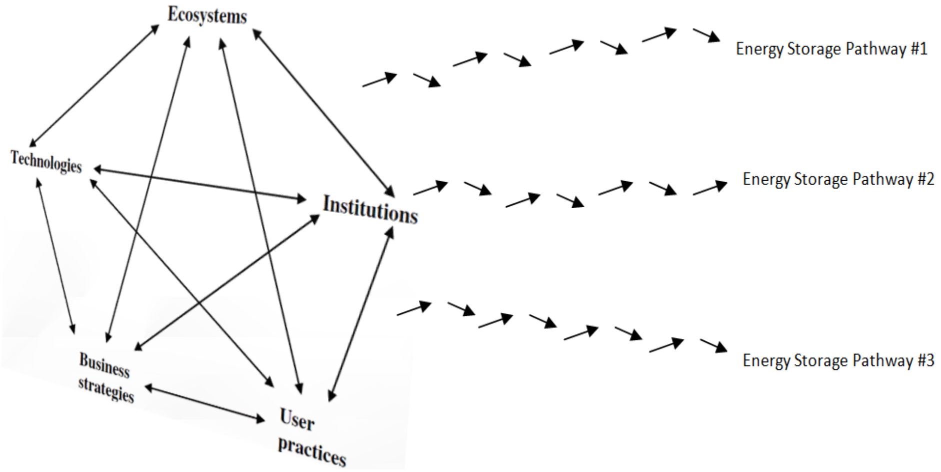
2.2 A coevolutionary framework

It is likely that established technologies such as pumped storage will continue to have an important role in future low-carbon energy systems. However, there is significant uncertainty as to the role that other electrical and heat storage applications will play as they are currently are at an early stage in the innovation chain and may only operate in niche contexts e.g. research and development (R&D) programmes and demonstration projects. As the UK moves towards a low-carbon energy system it is likely that the transition will not only involve dramatic changes in the technical architecture of energy systems but also in governance structures, institutional arrangements and actor networks which support the reliable delivery of energy services to end customers.

In developing a more systematic understanding of how a low-carbon energy regime might emerge we now consider in more depth the driving forces behind system change and the key contextual factors which are likely to influence storage deployment. Here we draw from Foxon (2011) who presents a coevolutionary framework on energy system transitions, identifying five dimensions – technologies, ecosystems, institutions, business strategies and user practices - which coevolve, through mutual causal influences, to shape alternative transition pathways (Figure 1). Foxon draws from socio-technical systems approaches but is critical of the representation of regimes as monolithic entities which provide 'overly structural explanations' of system change. Foxon's framework allows us to open up regimes to consider the role of different actors and sub-system processes.

The framework has already been deployed to analyse transition pathways towards a low-carbon energy system in the UK, exploring alternative governance models involving market, government and civil society actors (Foxon, 2013). As part of our pathway analysis in the next section we have adapted this framework to look at the implications of a broader system transition for a specific component technology, electrical and heat storage. Figure 1 points to the possibility of multiple pathways for energy storage which emerge as these system dimensions change and coevolve, creating new causal interactions in the system, altering selection criteria and creating new opportunities for actors to influence system change (Foxon, 2013). A key question we explore is how these system dimensions are likely to change in the future and how this might alter the selection environment for different energy storage technologies in the longer term. Drawing on Foxon (2011), the key components of the pathways are outlined below and in the following section we explore these pathway dimensions and how they are changing in the context of the low-carbon energy transition.

Figure 1: A coevolutionary framework for energy storage



Source: Extended from (Foxon, 2011)

- *Technologies* are 'methods and designs for transforming matter, energy and information from one state to another in pursuit of a goal or goals' (p.2262): Here we must consider the range of potential electrical and heat storage technologies in the context of the changing technical architecture of the system, in particular if large amounts of variable renewables are connected.
- *Ecological systems* are defined as 'systems of natural flows and interactions that maintain and enhance living systems' (p.2262): As outlined in the introduction, the UK has legally enshrined emissions reductions targets and as part of our pathway analysis in the next sections it is presumed that each of our pathways meet these targets.
- *Institutions*: 'ways of structuring human interactions' including 'regulatory frameworks, property rights and standard modes of business organisation' (p.2262). In our analysis we explore the changing structure of electricity markets in the UK as increasing amounts of low-carbon generation are connected to the system.
- *Business strategies* refer to 'the means and processes by which firms organise their activities so as to fulfil their socio-economic purposes' (p.2262). In the UK electricity storage is currently largely used to provide short-term operating reserve and other balancing services. The extent to which storage might deliver services to other markets and the role of new business models in facilitating storage deployment is explored.
- *User practices* are 'routinised, culturally embedded patterns of behaviour relating to fulfilling human needs and wants' (p.2263). As discussed above, pumped storage has become the dominant mode of storage and as such users have little direct interaction. However, if electricity systems become more decentralised and users become producers as well as customers small scale storage applications may become part of a user-led system transition. Public perceptions and the interaction between users and storage devices will therefore influence future pathways.

2.3 Methods

Drawing on Foxon's iterative method of socio-technical pathway development (Foxon, 2013), our analysis of energy storage pathways for the UK was conducted as a three stage process. Firstly a team of energy storage technology experts from the Universities of Leeds, Sheffield and Birmingham reviewed key storage technologies, selecting and documenting their characteristics, so enabling an investigation of their potential roles in a low-carbon energy system. As part of this process, a set of technology 'fact-sheets' were produced (available for download[1]) containing information on the technical and economic performance of each application (cycle efficiency, energy cost, duration, power capacity capital cost), along with their current status in terms of R&D and progress along the innovation chain. Also, during this initial phase, outline energy storage pathways were developed which were basic versions of the centralised, decentralised and user-led pathways presented in Section 4 of this paper. The initial pathways were constructed using a step-wise approach. First, a narrative for the wider developments in the energy system was proposed based on how a low-carbon system might develop at different scales. Secondly, the implications of these developments for balancing the grid and network constraints were considered. Lastly, a pathway for the development of energy storage was postulated as a solution to the issues identified in the first two steps, explicitly considering the coevolution of technologies, institutions, user practices and business strategies.

The second phase of the study consisted of a workshop which was primarily designed to provide a more detailed qualitative understanding of energy storage in a wider system context and to develop further our pathways drawing on insights from the attendees. The outline pathways were presented at the introduction to the workshop in order to guide the discussion which went on to focus on specific areas such as the structure of the electricity markets in the UK, the changing role of energy users and public perceptions of low-carbon technologies, the energy storage innovation system in the UK and internationally and the energy system challenges of decarbonisation. In all there were 29 attendees at the workshop including members of the core project team, along with prominent academics in the field, representatives from the energy industry, government, local authorities, and trade bodies.

The final step in the process was to review and analyse the outcomes of the workshop based on the notes taken by project team members. These were used as a basis to refine the description of the selection environment for energy storage (Section 3) and further develop the outline pathways (Section 4) and the discussion of them (Section 5). The main results were also presented in a report for the Centre for Low Carbon Futures (Taylor et al., 2012).

3. A changing selection environment for energy storage in the UK

As discussed in the section above, the contextual factors which influence storage deployment are likely to change dramatically as the UK moves towards a low-carbon future. In the sub-sections below we analyse this by discussing in more depth how the dimensions of the coevolutionary framework outlined above are changing as part of the ongoing and prospective energy system transition.

3.1 Technologies

3.1.1 Context of the energy system transition

Substantial reductions in greenhouse gas emissions will require massive changes in the way that the UK supplies and uses energy. Scenarios produced by the Government in its Carbon Plan (HM Government, 2011) show that the share of fossil fuel use in the primary fuel mix is expected to fall

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[1] http://lowcarbonfutures.org/pathways-energy-storage-uk

from around 90% today to between 13% and 43% by 2050. In contrast, the share of renewable energy could 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 (Table 1).

Table 1: The impacts of selected energy system developments on the market for energy storage

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
Widespread 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 district heating)
Significant introduction of plug-in hybrid and all-electric vehicles	Uncertain – could provide additional opportunities or compete for some services	Little impact
Availability of low cost and flexible fossil fuel generation	Negative for macro-level reserve and response functions	Negative for macro-scale inter-seasonal storage
Increased combined heat and power (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 with mainland Europe	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

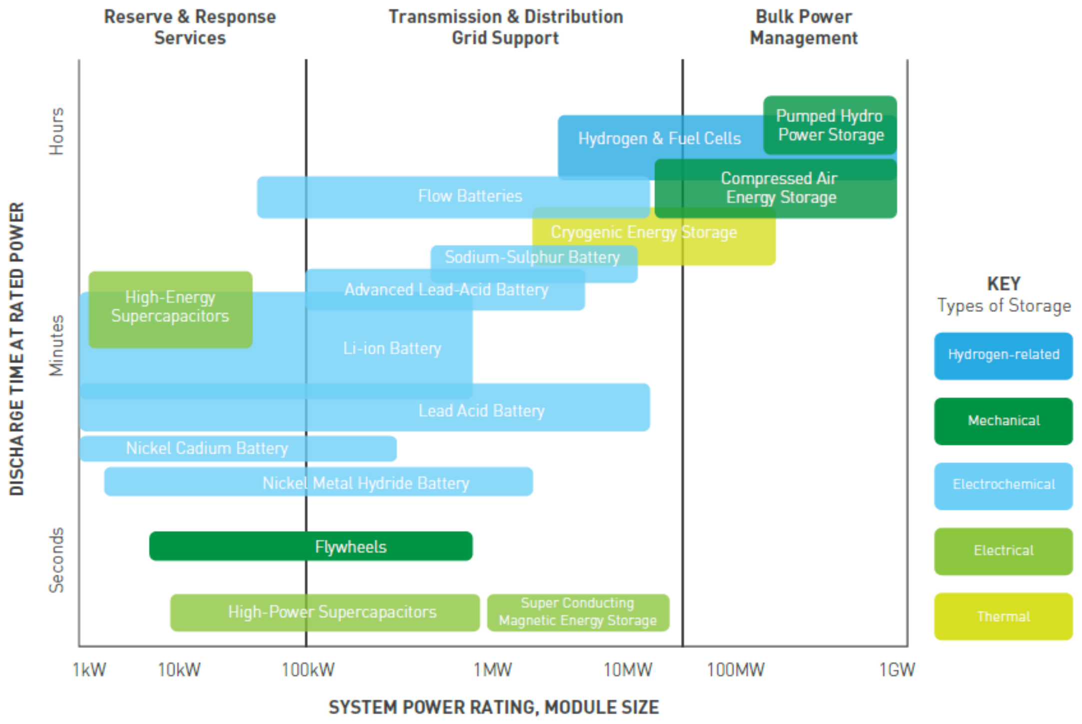
Note: This table combines findings from a variety of published studies and the outcomes of the workshop described in Section 2. “Positive” indicates a situtaion that is likely to create opportunities for additional electricity or heat storage, whereas “negative” is used for developments that could reduce opportunities for the deployment of the technologies.
Source: Adapted from Taylor et al. (2012)

3.1.2 *Energy Storage Technologies*

These changes in the wider energy system are likely to create new challenges for system balancing and energy security, potentially creating new windows of opportunity for storage technologies. 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 (Chen et al., 2009; Díaz-González et al., 2012; Evans et al., 2012; Fernandes et al., 2012; Hadjipaschalis et al., 2009). It is unlikely that a single solution will emerge in the near (or perhaps even distant) future given the wide variations in possible applications (Hall, 2008).

An ideal electrical storage technology 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 electrical storage systems are more or less suited to different application ranges (Figure 2). To date the push towards electrical storage is mostly from companies wishing to provide load levelling and frequency response correction with higher power/energy, centralised systems. Pumped storage and compressed air energy storage are both commercial technologies that can provide long-term large scale storage and may be joined by flow batteries, hydrogen and cryogenic energy storage in the longer term (Strbac et al., 2012b). Current research efforts on these technologies include examining new redox flow battery technologies (to lower costs), reducing the cost and improving the durability of hydrogen fuel cells and extending the operating range and usability of cryogenic energy storage. Where fast response is required then flywheels are currently commercially available, but supercapacitors also offer interesting prospects, including the longer-term possibility of significantly larger power devices.

Figure 2: Suitability of different electrical energy storage technologies for grid-scale applications



Source: Taylor et al. (2012)

There is also growing interest in decentralised, or distributed, electricity storage that may bring additional benefits. 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. For the smaller and scalable technologies – such as batteries, fuel cells, supercapacitors and flywheels – demand from the transport industry is spurring parallel research efforts, which should reduce the time to commercialisation and increase the rate of technical developments. Key research areas include extending the useful operating life of all battery storage systems and developing more accurate state of charge and state of health prediction algorithms, as well as improving the safety of high temperature molten metal batteries and investigating newer battery chemistries, such as sodium-ion (reducing dependence on lithium resources) and lithium-air (which has a very high energy density). The use of second-life lithium-ion batteries could also be an interesting option if electric and hybrid electric vehicles start to take significant market share.

In comparison to electrical storage, heat storage technologies have been the focus of much less research. The characteristics of thermal energy storage can be defined in terms of capacity, power, efficiency, storage period, charge/discharge time and cost (ETSAP and IRENA, 2012). Hot water tanks, utilising sensible heat[2], are a fully commercial technology from the scale of individual households to district heating schemes. Larger storage volumes and longer storage periods (up to months) can be achieved by storing hot (or cold) water underground. 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 a variety of phase change materials are being explored for thermal energy storage applications, either in containers as a standalone store or included in building materials. Thermochemical storage is another option with the advantages of high 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.

3.2 Ecosystems

Concerns over the impact of greenhouse gas emissions on ecological systems are one of the main drivers that could create opportunities for further energy storage, while a wider variety of environmental impacts associated with storage may also be a factor influencing technology selection.

The desire of many countries to substantially decarbonise their energy systems is driven by concerns over the effects of greenhouse gas emissions from fossil fuel combustion on the climate and consequent deleterious impact on ecosystems. Reducing fossil fuel use, with its inherent capacity for storing energy, is likely to increase the opportunities for electricity and heat storage. In addition, most energy storage technologies emit very little or no greenhouse gas emissions during use, the main exception being some types of compressed air energy storage that involve fossil-fuel

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[2] Sensible heat is the energy released or absorbed by a material as a result of a change in its temperature.

combustion. There is therefore a (potential) correlation between the level of greenhouse gas emissions reductions, the share of fossil fuels and the opportunities for energy storage.

The broader environmental impact of energy storage technologies is highly variable, although most are considered relatively benign in comparison to the impacts from fossil fuel electricity generation. Amongst electrical energy storage technologies, cryogenic energy storage is unique in that it can provide environmental benefits by removing contaminants in the air and CO_2 capture during the charging process. A number of the chemical-based electrical storage mechanisms have potentially high environmental impacts dependent on their exact chemical composition – there can be dozens of subtypes for a single technology. However, it is hoped that through improvements in recycling processes toxic waste can be reduced. Some concerns have been recently expressed over the safety of high temperature sodium-sulphur batteries. Other considerations are the impact on landscapes of pumped storage systems, and the negative effect on human health associated with strong magnetic fields such as in superconducting magnetic energy storage.

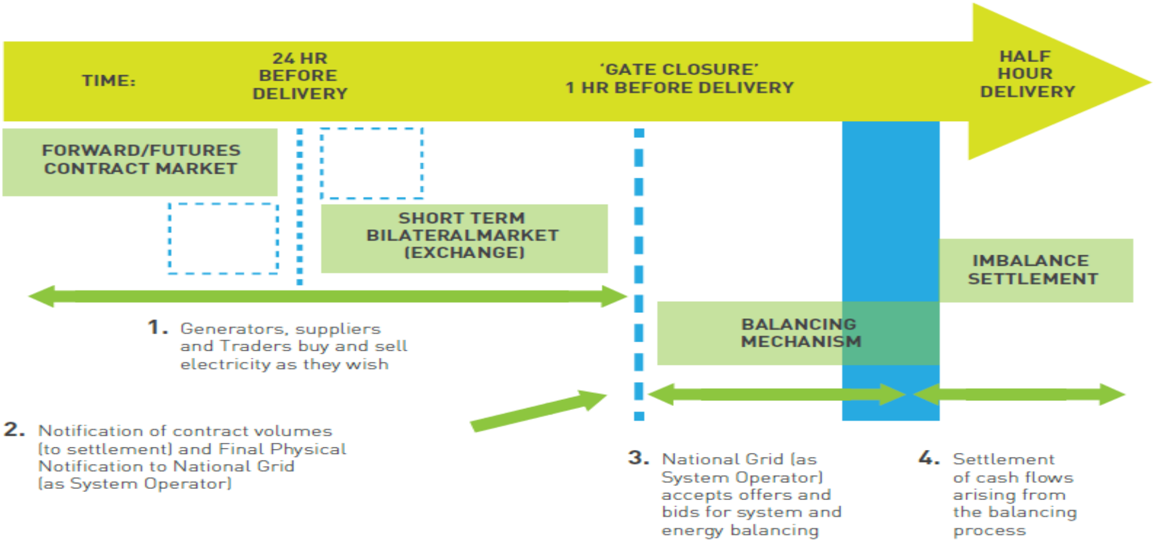
For thermal energy storage, the most significant potential environmental impacts are from underground systems, which may pose risks to the ground water system if not managed properly (Bonte et al., 2011).

3.3 Institutions

As has been outlined, pumped storage plays a limited but important role in the current electricity system, particularly at peak times. There is approximately 2,800 MW of capacity on the system which can be called upon for a range of services including 'peak demand levelling, fast reserve, … emergency grid restart services' (Postnote, 2008). In order to understand the role that storage plays in the current system and its prospective role in a low-carbon energy system it is important to have an overview of the structure of energy markets and how they are changing.

The Great Britain (GB) high voltage transmission network is divided into three parts, all owned by publicly listed companies: the two Scottish networks are owned by Scottish Power and Scottish and Southern while in England and Wales the network is owned by National Grid who, as System Operator (SO), is also responsible for ensuring that there is sufficient capacity on the system to meet demand. Although electricity suppliers are incentivised to procure adequate capacity to meet demand on an ongoing basis, (predominantly through bilateral trading between the retail and generation divisions of the large suppliers), the SO intervenes at 'Gate Closure'- one hour before each trading period – to ensure that there is a continuous balance between supply and demand. From this point forward a 'Balancing Mechanism' operates where National Grid purchases the required balancing services which can be storage, generation, demand flexibility or interconnector capacity (Taylor et al., 2012) from a range of registered providers including storage operators. This market structure is illustrated in Figure 3.

Figure 3: The British Electricity Trading Arrangements



Source: National Grid (2011a) – © National Grid plc, all rights reserved.

Although there is adequate capacity currently on the system to deal with imbalances, in the medium and long term future, as existing coal-plants are retired due to environmental constraints and increasing levels of renewables are connected to the system, new challenges will be faced by the system operator. National Grid estimate that in a scenario with 25 GW of wind generation connected to the transmission networks by 2020, operating at a 30% load factor, the SO will need to increase its operating reserve requirement from the current 4 GW to somewhere in the region of 7 GW (National Grid, 2011b). In theory this will include increasing levels of demand response, interconnector capacity, gas-fired back-up generation and storage. As Table 2 illustrates, it is likely that a mix of these solutions will be required, as they each possess different systems attributes.

Recent proposals for Electricity Market Reform (EMR) made by DECC have recognised the need for policy change to reflect the greater levels of *reserve and response* that will be required in a low-carbon electricity system. A capacity mechanism has been proposed which will introduce a new capacity market to incentivise investment in generation, storage, interconnection, demand side response[3]. As discussed above, these solutions can be called upon by National Grid to maintain system security, particularly at peak periods. As part of the proposed market the required volume of capacity will be determined centrally by the SO and participants in the market will compete in periodic auctions to win contracts to provide services and receive payments.

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[3] EMR consists of a number of proposed changes that are designed to enable large-scale investment in low-carbon generation capacity in the UK and deliver security of supply, in a cost-effective way. At the time of writing, these proposals are being considered by Parliament and so still could be subject to change. Along with the capacity market, the changes include long term contracts for low-carbon generation and a guaranteed carbon price floor to 2030 which are designed to provide long term certainty to investors in low-carbon generation.

Table 2: Advantages and disadvantages of different sources of system flexibility

Source of system flexibility	Advantages	Disadvantages
Storage	• A diverse set of technologies that provide multiple system-wide services • Can be deployed at all scales of the system • Ability to provide fast response and two-way arbitrage	• Many storage applications are unproven and at an early stage in the innovation chain • Lack of certainty over revenue streams • Regulatory barriers
Interconnection	• Proven technology which facilitates market integration with the EU • Ability to provide two-way arbitrage	• Relies on a price differential between markets • Similar weather systems can affect neighbouring markets • Lack of certainty over revenue streams and regulatory barriers
Demand Response	• Less capital intensive than other solutions • Can offset investment in network capacity and improve utilisation of generation	• Typically relies on human response, so potentially less reliable than technology based solutions • Market is immature and the potential for and costs of domestic scale demand response is unproven
Backup generation	• A proven technology and operating in a positive investment climate	• Potentially high and variable cost of natural gas • Contributes to CO2 emissions

Note: This table combines findings from a variety of published studies and the outcomes of the workshop described in Section 2
Source: Adapted from Taylor et al. (2012)

The main reason for introducing a capacity mechanism is that as old fossil fuel generating plant come off stream over the next decade there will be a tightening of capacity margins which, although currently adequate at approximately 16%, are projected to decline to somewhere in the region of 10% or below by the end of the 2010s (DECC, 2011a). In the liberalised market structure prices alone have been relied upon to provide signals to investors and this has been sufficient to deliver significant levels of new gas-fired generating capacity which serves as the system marginal plant. However, as increasing levels of renewable plant is connected to the system over the coming decades, it is likely that the load factors of gas generation will decrease, becoming a potential barrier to investment and a threat to energy security. Recognising that competitive auction processes tend to favour incumbent technologies, the Government is proposing transitional arrangements which it hopes will better enable the participation of demand response and smaller scale storage in the capacity mechanism. Nevertheless, the extent to which the new arrangements might open a window of opportunity for increased storage capacity on the system is still uncertain.

Developments in the heat market are also likely to have a significant impact on the role and nature of energy storage in a low-carbon energy system. In the UK energy system approximately 81% of domestic space heating is met by gas-fired boilers with renewable heating accounting for only 1%. In the medium and long term future this is likely to change dramatically as by 2020 it is expected that 12% of the UK's heat demand will be from renewables, and by 2050 there will be near total decarbonisation of emissions from buildings and a 70% reduction in industry emissions (DECC, 2012). The market for low-carbon heat in the UK is currently at an early stage of development; however in recent years there has been some growth with a 17% increase in renewable sources in 2010 which was primarily biomass and heat pumps in new builds (DECC, 2012). In an effort to stimulate deployment the government has begun to introduce a subsidy scheme for renewable heat called the Renewable Heat Incentive (RHI) on a phased basis beginning with the non-domestic sector and near commercial technologies, with phase II supporting domestic technologies (DECC, 2011b)[4]. DECC's recently published heat strategy (DECC, 2012) also highlights the potentially significant role that district heating could play in a low-carbon future, particularly in densely populated urban areas. Analysis in DECC's 2009 Heat and Energy Saving Strategy showed that CHP and district heating (CHP-DH) investments in areas with a heat density above 3000 kW/km^2 could be commercially viable and potentially supply 5.5 million properties (DECC, 2009), however there are significant economic and institutional barriers to be overcome if the UK is to develop district heating to a similar degree as Nordic countries, for example.

Perhaps due to the early stage of development of the low-carbon heat market in the UK there has been relatively little discussion of the potential role of heat storage in this context. However there is a recognition that as the capability to store energy in the form of natural gas in the grid becomes diminished, there will need to be new ways of finding flexibility (DECC, 2012). This may be in the form of storage at the site of demand as part of more intelligent heating controls which help to even out daily or inter-seasonal demand fluctuations. Lessons can be learned from more mature heat markets such as Denmark where thermal storage is being used in conjunction with CHP-DH systems, allowing CHP operators to engage in arbitrage by generating excess electricity during peak periods and storing it for subsequent distribution during periods of peak heat demand (Toke and Fragaki, 2008). As the Danish system has a high penetration of wind power, during periods of high wind and low demand this can help to balance the system and improve the integration of renewables. The role of storage in creating these types of synergies between the heat and electricity markets could play an important part in the transition towards 'smart energy systems' (Lund et al., 2012).

3.4 Business Strategies

Under the current liberalised market structure, as described above, storage operates in the competitive, rather than the regulated monopoly, component of the value chain. This means that the revenue stream from storage investment is from its arbitrage value i.e. storing electricity when electricity prices are low during off-peak periods and selling it as a system service to the SO during peak periods. The value of storage to the system lies in its ability to provide fast response as it can be called upon by the SO to meet short term fluctuations during peak periods.

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[4] Renewable heating technologies that are to receive support include biomass boilers, solar thermal, energy from waste combustion (biomass portion of waste), heating from biogas combustion – gas from waste, ground and water source heat pumps, biomethane injection into the gas grid, deep geothermal, renewable district or community heating (biomass), renewable CHP, for biomass, biogas and geothermal. Different levels of support are to be given based on the technology type and size.

As the electricity system is increasingly decarbonised and as the flexibility provided by fossil fuel storage and generation is diminished, the system benefits of storage will potentially become much more valuable. As such it is likely that the application of electrical and heat storage can contribute to a reduction in the overall system cost of the low-carbon transformation - in terms of investment and operation - by; reduced costs of reinforcing the transmission and distribution networks, reduced curtailment of renewables, improved asset utilisation and reducing network congestion.

However, under the current market arrangements, where there is strict business separation, or unbundling, across the regulated monopoly (transmissions and distribution) and competitive (generation and retail) areas of the system, it is difficult to allocate the risks and benefits of investment in storage technologies. Similar issues are faced when looking at how to realise value from demand response and therefore, from a ‘whole systems perspective’, it is clear that novel forms of contractual arrangements and business models are required in order to adequately value these new forms of system flexibility which will be increasingly important in a low-carbon context (it is arguably the case that the EMR proposal for a capacity mechanism does not fully address this issue). A number of proposals have been suggested including the participation of distribution network operators (DNOs) in the electricity markets where new arrangements allow them to act as distribution system operators (DSOs) similar to a TSO but at a regional/local level, whereby the output of decentralised generators, demand response and storage are actively managed in order to optimise the operation and planning of distribution networks (see, for example, EDSO (2012)). An alternative novel business model arrangement has been proposed by He et al. (2012) where storage capacity is sold through repeated auctions during a given time period and returns can be optimised either to maximise profits from arbitrage, minimise costs etc.; thus enabling the investor to ‘capture the overall value of storage by providing multiple services to the power system’ (p. 1584). In a decentralised storage pathway there may be a requirement for aggregators to pool the resources of many small scale applications operating in such a market. Developing new business and commercial arrangements will be one of the key challenges to the deployment of storage technologies, particularly at the distribution network scale where it could potentially have the most significant overall system value.

This also has relevance to the heat market in the UK. As it is currently underdeveloped the potential value of thermal storage to the system in terms of flexibility and the creation of synergies between the electricity and heat supply are not recognised. In the Danish case cited above, where thermal storage at CHP plants helps to smooth system peaks and integrate wind power, the presence of aggregators who pooled the output of many small CHP units and a tariff structure which paid higher prices for CHP electrical output during peak periods enabled investment in thermal stores (Toke and Fragaki, 2008). In the event that electrical and heat storage becomes deployed at the domestic scale, such a role could potentially be fulfilled by small scale energy service companies (ESCOs) who are likely to have a better understanding of end-user practices and routines, and as such effectively optimise the potential system benefits.

3.5 User practices

Here we focus mainly on issues relating to domestic and community-level forms of energy storage, given that large-scale, system level issues are considered above. From a domestic and community perspective, large scale energy storage infrastructure may have industrial connotations, regardless of benefits to end-consumers. We may assume that equipment out of sight, below ground or low level is likely to be preferable to more visible infrastructure that draws attention, but this is only an assumption – as in the case of carbon capture and storage, any underground storage perceived as presenting a risk, even if slight, may become a focus of objection if there are other, predisposing factors (Oltra et al., 2012). Moreover, 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. Positive perceptions of community-level infrastructure may be more plausible in rural locations with obviously-defined communities, particularly where the community is not on a main gas grid or in some other respect energy insecure (Upham and Speakman, 2007). Appropriate messaging is important when introducing new energy technology cases and there are established principles for this, amongst which trust in the message source is particularly important (Brunsting et al., 2011). 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 or more generally where people have strong place attachments (Devine-Wright, 2009) 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. Based on experience of consumer uptake of micro-renewables and energy efficiency products, affordability, controllability, performance, aesthetics and fit with the domestic or work habits will likely be important (Roy et al., 2007). 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. If we assume that microgeneration technologies are analogous to domestic storage options, then without a strong incentive to install, uptake will likely be low to modest. Experience with domestic-focussed feed in tariffs shows the importance of financial subsidies as an enabler for microgeneration installation; even where consumers have strong pro-environmental attitudes, without subsidies only a minority can or will install (Upham, 2011). 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 (ibid), 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 models and lessons from the community wind sector are relevant (e.g. TLT Solicitors, 2007; Walker, 2008).

4. Bringing the framework together: Pathways for energy storage

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 based on the coevolutionary framework described earlier. In doing so, our approach builds on a recent review of low-carbon scenarios which calls for a better understanding of the role of different stakeholders and social processes to be built into scenario methodologies (Hughes and Strachan, 2010). 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.[5] 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

We also recognise that the narratives are based on certain assumptions about actor behaviour and underlying social processes which in reality are more complex and contested than is presented below. The pathways approach, although a simplification, serves as a conceptual tool to explore the diverse roles that energy storage technologies might play in a low carbon energy system. Therefore, the pathways themselves are for illustrative purposes only and should not be seen a predictions of the future.

4.1 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. This lack of trust in the capacity of dominant industry players to deliver may be accompanied by the emergence of strong financial drivers, in which increasing fuel prices drive domestic and community level action.

In this pathway, local bottom-up diversity of solutions flourish, with community leadership providing decentralised and microgeneration and energy conservation options (Figure 4). Energy supply companies roll-out smart meters and introduce new 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 photovoltaic systems, micro-wind turbines 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.

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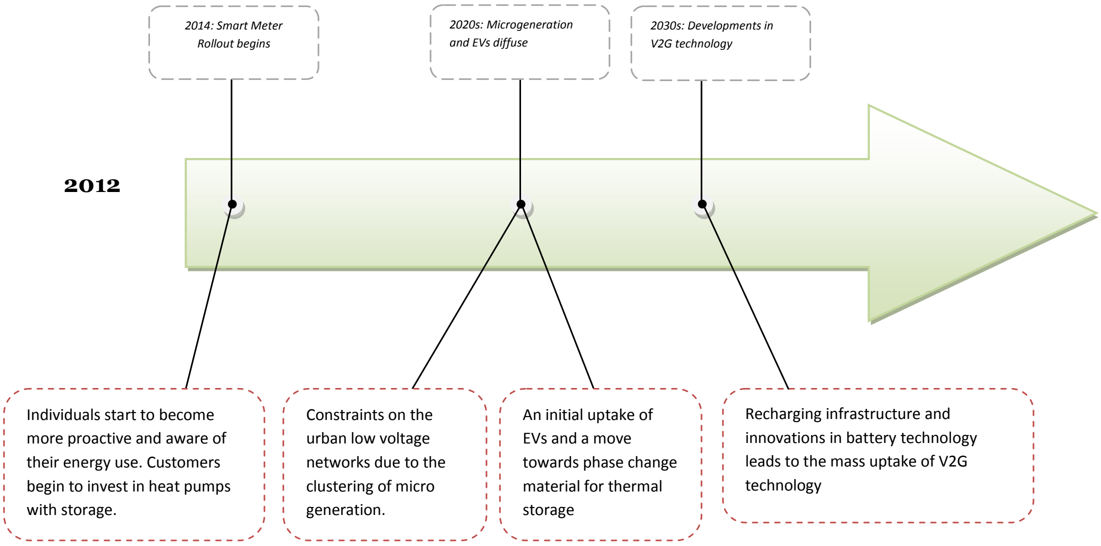
[5] Since all pathways are assumed to meet the UK's long-term greenhouse gas emissions reduction target, the impacts of alternate developments in the ecosystem dimension are not considered further.

Figure 4: Summary of key developments in the user-led pathway



Source: Adapted from Taylor et al. (2012)

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 see themselves 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. 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 vehicle-to-grid (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 microgeneration systems and to act as a buffer between the grid and electric vehicle charging (thus avoiding peak electricity prices).

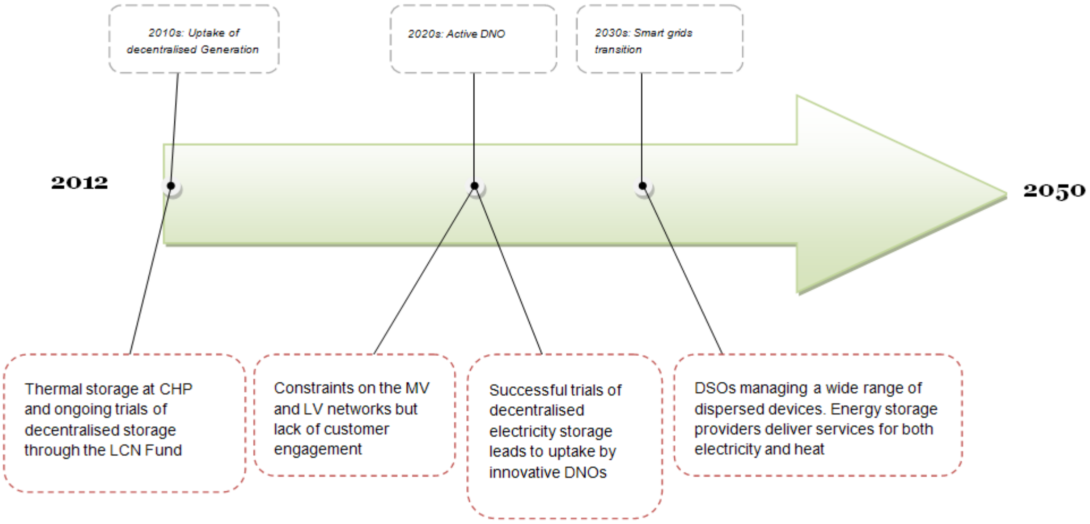
4.2 Decentralised storage

Under a decentralised pathway, meso-scale community and city based energy provision become 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 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 (Figure 5). 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 district heating 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 combined heat and power, allowing operators to optimise their plant. As DNOs begin to actively manage their systems they utilise this to help manage constraints. During the 2020s, following the success of the regulator's innovation initiative, the Low Carbon Networks 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.

Figure 5: Summary of key developments in the decentralised pathway



Source: Adapted from Taylor et al. (2012)

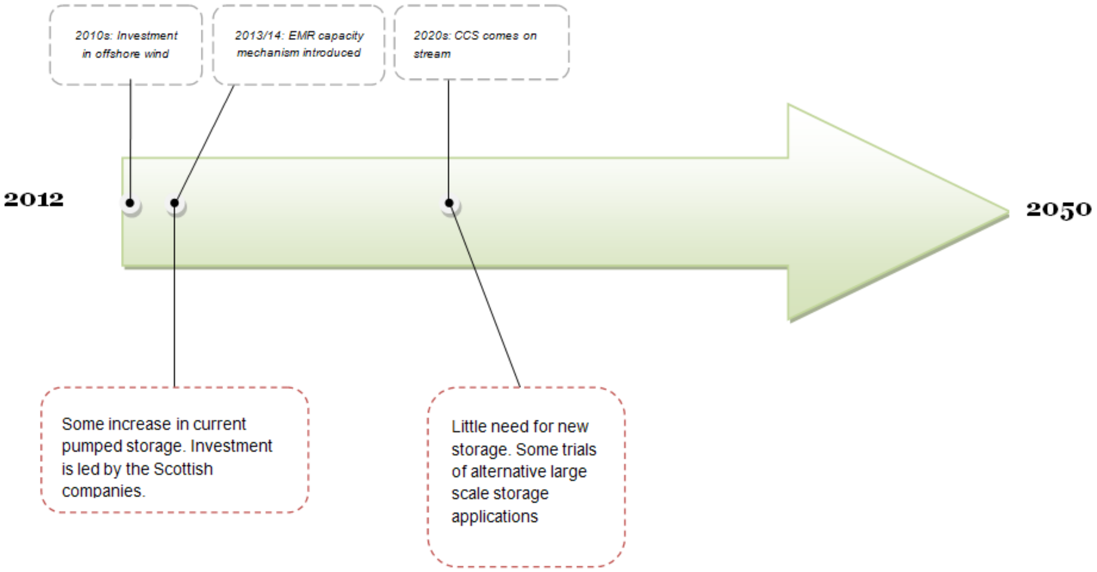
4.3 Centralised storage

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 15% of all energy produced from renewables (Figure 6). 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.

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, cryogenic energy storage and redox flow batteries receive R&D funding and there is interest in hydrogen as a longer-term option.

Figure 6: Summary of key developments in the centralised pathway



Source: Adapted from Taylor et al. (2012)

5. Discussion of the pathways in the context of the coevolutionary framework

The pathways described in the previous section have been constructed to explore three different scales – micro, meso and macro - at which energy storage may play a role in a low-carbon energy system. The technologies, business strategies, institutions and user practices that coevolve under each of these pathways are summarised in Table 3.

The following discussion highlights the coevolutionary processes that are most relevant under each of the pathways. We also give some consideration to 'branching points'[6] in order to identify some of the key risks associated with the pathways. Policy responses that can help mitigate these risks are

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[6] A branching point is a point at which internal or external stresses, stimuli or triggers mean that key actors make choices that will determine whether a particular pathway is followed or not (Foxon, Pearson et al. 2013).

also described i.e. what actions should be taken now in order to help realise a particular pathway and/or mitigate against risks and/or make the pathways more resilient?

In the user-led pathway, electricity and heat storage are deployed at a building level as part of a trend which sees consumers take a much greater interest in, and control over, the supply of their own energy. Such a scenario would require technology developments in micro-level energy storage to co-evolve with user practices that embrace such technologies. Initially, the storage technologies could be relatively simple, such as large hot water tanks, but later would develop into more complex devices including advanced heat storage and battery systems and smart battery management. A virtuous circle could therefore be created by demand from consumers leading to new technology developments so stimulating further increases in demand for storage technologies. Such developments would be supported by innovative institutional arrangements and business strategies, such as time of day pricing of electricity and “aggregators” who trade in the electricity market on behalf of customers.

Table 3: Summary of the pathway characteristics

Pathway	Storage Technologies Deployed	Business Strategies	The role of users in the pathway	Institutional changes required to facilitate pathway
User-Led	Domestic level thermal storage and V2G	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. Less uptake of DSM and micro generation	Changes to regulations to facilitate DSOs
Centralised	Large scale pumped storage on the transmission grid	Some new investments by Scottish companies	Passive users. Sector is dominated by the ‘big six’	EMR capacity mechanism stimulates some storage investments

Source: Adapted from Taylor et al. (2012)

A major risk associated with this pathway is that consumer take-up of energy storage technologies falters after the first phase of early adopters, due to a lack of interest in, or low acceptance of, the technologies amongst the broader public. Such a lack of engagement by consumers could lead to the pathway being limited in its ability to deliver emissions savings from households or even failing completely, possibly with the result that a branching point is created onto one of the other pathways. The implications of such developments could therefore be that energy storage technologies fail to play a major role in the future UK energy system, or that decentralised or centralised storage technologies become the dominant form. Mitigating the risk of this pathway failing would therefore include strategies to subsidise and help to build confidence in the installation of storage technologies, using measures such as zero interest repayment plans and installer certification schemes as described in Section 3.5.

In the decentralised pathway, a localism agenda sees community and city-based energy provision become a much more prominent feature of the UK energy system, with local authorities, local energy companies and energy service companies all playing an active role. At the heart of this pathway is the coevolution of institutional structures and business strategies, which provide incentives for the more active involvement of DNOs in managing their distribution networks and alliances of local authorities and energy service companies to roll-out a greater level of community-based heating. Successful early demonstration of the business case for this approach would be crucial in ensuring its widespread adoption. This would also need to be supported by developments in storage technologies, such as large-scale battery and heat storage systems, including underground systems. Engaging consumers, while less significant than in the user-led pathway, could also be important in the case of public acceptance of heat provision from community-based schemes.

An important risk to this pathway could be that the business case is not universally recognised and as a result a piecemeal approach develops, with some cities and local energy companies embracing the concepts, while other areas lag behind. This could lead to a situation where smart grids, which incorporate dynamic energy flows and utilise storage technologies, develop in a fragmented fashion and only in a small number of areas of the system. This lack of a national smart grid roll-out strategy could in turn lead to national emission reduction targets coming under threat due to a failure to cope with a more complex and decentralised energy system in an intelligent and efficient manner (Bolton and Foxon, 2011; Foxon et al., 2013). One possible response would then be a branching to the centralised storage pathway if central government decided that it needed to take more control to ensure that the targets were reached. These risks could be minimised by ensuring that storage technologies form an integral part of LCN fund trials and ensuring that the next price control review, due in 2015, provides incentives for DNOs to actively manage their networks through procuring third-party services, such as storage and demand-side management. In addition, local authorities could be encouraged to identify the most appropriate role for district heating in their area and support its deployment. This could be through a combination of activities including heat mapping, energy planning, encouraging co-location of potential heat customers and suppliers and offer brokering services, providing planning support and guidance and prioritising cost-effective deployment in their own building stock.

The centralised pathway can be seen as representing a natural development of the current energy system, but is dependent on an institutional structure that provides the necessary incentives to encourage investment in large-scale low-carbon generation and storage coevolving with businesses strategies that respond to those incentives. Most of the centralised storage technologies that are deployed initially in this scenario are already commercially available, although further R&D would be needed to ensure that less mature designs are available post 2030. The involvement of users is much less than in the other two pathways.

A potential risk to this pathway concerns the attractiveness to investors of the electricity market arrangements. The pathway could come under significant threat if, after a few years, it becomes apparent that due to poor design, the electricity market reform fails to provide strong enough investment signals for large-scale low-carbon technologies and so the pace of electricity decarbonisation is too slow. This could result in greater intervention by the government to shore-up the pathway by issuing long term contracts for defined amounts of low-carbon capacity, with centralised storage becoming part of that portfolio. Alternatively, the pathway could fail to deliver centralised storage, with new natural gas plant built to meet the looming supply-demand gap and to provide back-up generation. This may mean that carbon targets are missed, but security of supply is maintained.

The key risk mitigation strategy for this pathway is to ensure that the design of the EMR provides an environment conducive to low-carbon investment and this could include elements such as a credible approach to underwriting the contracts for differences, setting the carbon price floor at an appropriate level and ensuring the capacity mechanism provides a level playing field for demand-side, storage and back-up fossil generation options.

6. Conclusions

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. Drawing on insights from the system innovation and socio-technical transitions literatures, we have utilised a framework based on coevolutionary thinking (Foxon, 2011) to analyse how changes in ecosystems, user practices, business strategies, institutions and technical systems are creating a new selection environment and potentially opening up the energy system to new variations of storage for electricity and heat. These dimensions of the energy regime, we argue, will coevolve in mutually reinforcing ways to create alternative pathways for the energy system which in turn have different flexibility requirements and imply different roles for storage technologies beyond the current centralised pumped storage dominant design. Using this framework we analysed the contextual factors which might influence the deployment of storage technologies in the UK and developed three pathways – user led, decentralised and centralised - which illustrate potential long-term trajectories for this set of technologies in a low-carbon energy system.

This analysis illustrates that the overall development of the UK energy system will be key in determining the need and role for energy storage. Increased electricity generation from variable renewable sources, such as wind, combined with the electrification of heat in homes are two 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 vehicles; the availability of cheap and flexible fossil-fuel generation; the extent of combined heat and power 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. The types of energy storage technologies that are ultimately most successful will have strong bearing on the pathway that is followed. At the moment large-scale electricity storage technologies are most prevalent amongst the commercial technologies and this may lead to a lock-in to a centralised pathway unless more R&D is spent on the decentralised and user-level alternatives, including advanced heat storage.

Energy storage currently faces a number of significant barriers relating to institutional arrangements and business practices. A number of studies have shown how storage can bring benefits across the electricity system, but also highlight that currently 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 network and generation activities so that transmission and distribution operators cannot own energy storage facilities and use them in the trading environment. Finally, storage may offer greatest value to the system when placed closest to the source of demand. However, capturing this value will require new institutional and business arrangements.

Public attitudes towards energy storage could be crucial in determining the future deployment of energy storage, 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.

We believe this type of qualitative analysis provides a useful complement to the recent quantitative modelling studies that have looked at the value of energy storage to a low-carbon energy system (Grünewald et al., 2011; Strbac et al., 2012a; Strbac et al., 2012b; Wilson et al., 2011). The coevolutionary framework and pathways approach has allowed us to explore storage in its wider system context and to analyse how different storage technologies, as part of a suite of solutions incorporating demand response, interconnection and back-up plant, could contribute to delivering flexibility in a low-carbon energy system. Taking a long-term pathways perspective has illustrated the potential risk of lock-in to sub-optimal pathways if policy makers and regulators develop strategies based solely on current market conditions. Many promising storage technologies are currently at an early phase of the innovation chain and if their potential value to the energy system is to be realised, long-term strategies need to be put in place which create pathways to deployment.

Our approach of course has its limitations as these are outline pathways which require significant in-depth further analysis. Firstly, the pathways presented are for illustrative purposes and are idealised simplifications of a complex reality. A next step would be to analyse how these pathways are unfolding in real-time, potentially focusing on the emerging synergies and tensions. Secondly, we have pointed to the fact that there has been little or no published research into the interaction of domestic end-users with storage technologies and public perceptions of both centralised and decentralised applications. Finally, the energy system implications and economic costs of our pathways could be interrogated in more depth using formal modelling to complement our qualitative insights.

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