Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Energy storage in the UK electrical network: Estimation of the scale and review of technology options

Ian Allan Grant Wilson [a], Peter G. McGregor [b], Peter J. Hall [a,*]

[a] Department of Chemical and Process Engineering, University of Strathclyde, Glasgow, UK
[b] Fraser of Allander Institute, Department of Economics, University of Strathclyde, Glasgow, UK

ARTICLE INFO

Article history:
Received 29 August 2009
Accepted 15 March 2010

Keywords:
Rechargeable storage
Fossil-fuel storage
UK energy storage

ABSTRACT

This paper aims to clarify the difference between stores of energy in the form of non-rechargeable stores of energy such as fossil-fuels, and the storage of electricity by devices that are rechargeable. The existing scale of these two distinct types of storage is considered in the UK context, followed by a review of rechargeable technology options. The storage is found to be overwhelmingly contained within the fossil-fuel stores of conventional generators, but their scale is thought to be determined by the risks associated with long supply chains and price variability. The paper also aims to add to the debate regarding the need to have more flexible supply and demand available within the UK electrical network in order to balance the expected increase of wind derived generation. We conclude that the decarbonisation challenge facing the UK electricity sector should be seen not only as a supply and demand challenge but also as a storage challenge.

1. Introduction

The shift to low-carbon electricity will rely on the potential deployment of a number of technologies including renewables, nuclear, and coal/gas combustion with carbon capture and storage (CCS). Of these, nuclear and coal/gas with CCS, fit into the existing network paradigm of electricity being generated by a relatively small number of centralised large-scale (~GW) power stations linked to a central grid. The increased level of renewable energy capacity that is expected to be connected to the UK electrical network poses several new challenges. There is no guarantee that periods of electricity generation will coincide with periods of electricity demand. The relationship between wind power output and electricity demand was examined by Sinden (2007). In short, renewables that are dependent on wind, solar radiation, tidal or wave energy are rarely load following. These weather- and tidal-dependent technologies are classed as non-dispatchable; their outputs cannot be increased to match demand if the energy inputs are not available, in contrast to renewables based on biomass or geothermal energy that can be dispatched within the limitations of their technologies. It is estimated that contributions of above 20% from non-dispatchable renewable energy will require much greater balancing and system reserve requirements than contributions below 20% (Gross et al., 2006).

One possible solution to reduce the impact of connecting greater amounts of non-dispatchable renewable energy to system reliability is to provide greater energy storage within electrical networks. This paper defines any storage device that can be charged using electricity as rechargeable storage or R-storage, and defines non-rechargeable storage as stores of energy that cannot be charged using electricity. Examples of non-rechargeable storage include the calorific energy of fossil-fuels or biomass, which although they provide a store of energy that can be partially converted to electricity, the reverse is not true. Confusion can arise as depleted stores of fuels can themselves be “recharged” with more fuels. This paper will use the terminology F-storage for the electricity content of the non-rechargeable stores of energy contained in fuels, F-storage is therefore not only dependent on the energy content of the fuels, but also on the conversion efficiencies of converting this energy into electricity. Fuels are not used to store excess electricity, they are utilised to provide a convenient and economical store of energy to be converted into electricity. As a simple analogy, rechargeable batteries (secondary batteries) would be classed as R-storage and non-rechargeable batteries (primary batteries) would be classed as F-storage in this paper. The units for R-storage and F-storage are multiples of kWh, i.e. the amount of electrical energy stored, whereas the units for power output are multiples of kW. Network will be taken to mean the UK electricity network throughout this paper unless otherwise specified.

The question of how much energy needs to be stored, and the time scale over which it should be stored, are important to

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[*] Corresponding author.
E-mail address: p.j.hall@strath.ac.uk (P.J. Hall).

0301-4215/$ - see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.enpol.2010.03.036

Please cite this article as: Wilson, I.A.G., et al., Energy storage in the UK electrical network: Estimation of the scale and review of technology options. Energy Policy (2010), doi:10.1016/j.enpol.2010.03.036

examine in order to provide a stable and resilient electricity network able to supply electricity of a sufficiently high quality suitable for a modern industrialised economy. The aim of this paper is to add to the informed debate regarding energy storage in the context of the UK electricity network.

Section 2 provides a background to fuels and networks, Section 3 examines the present-day storage of the network and Section 4 considers technology options in the MWh–GWh range. Section 5 discusses whether it is necessary to replace the stores of energy contained within UK fuel stores (F-storage) with rechargeable storage (R-storage) and Section 6 is a brief conclusion.

2. Background to fuels and networks

Fossil-fuels provide a convenient store of calorific energy that can be converted into electricity on demand, and electrical generators that use fossil-fuels are classed as dispatchable; their output can be controlled within the limitations of the generating technology. Fossil-fuels are accorded a considerable importance at a political level throughout the world. An example of the strategic importance of the energy stored in fossil-fuels can be found in the EU Directive 2006/67/EC (EU, 2007), which legislates that ''Member States are required to build up and constantly maintain minimum stocks of petroleum products equal to at least 90 days of the average daily internal consumption during the previous calendar year''. Although oil provides a large share of the primary energy inputs for European transport networks rather than electrical generation, this legislation could be viewed as a political response rather than a market response to provide a degree of security of supply within the European petroleum products market. This implicit level of storage is an indication not only of the importance of oil as a primary energy input, but also of the risks associated with the length of the supply chains. This type of implicit obligation for the level of storage of petroleum products has not been repeated with EU directives regarding gas (2004/67/EC) or electricity (2005/89/EC), where the amount of storage is determined by member states. However, new regulations have been adopted by the EU commission (COM/2009/0363 final) in July 2009, partly in response to the Russian–Ukrainian gas crisis of January 2009, in order to provide a further degree of security of supply to the EU gas markets, and as of 26/1/10 the regulations require adoption by the European Parliament (COD/2009/0108). ''The main objective of the proposal is to increase the security of gas supply by creating the incentives to invest in necessary interconnections to meet the $N-1$ indicator, as well as the reverse flows'' (EU, 2009).

Fossil-fuels and electricity both can be thought of as energy vectors, albeit with geologically different timeframes of the storage and release of energy. Amongst other things, fuels have the attribute of being economic stores of energy, whilst the electrical charge needed to create the flow of electricity has the attributes of being extremely difficult and expensive to store, usually by separating two oppositely charged conductors with an insulator (capacitors and electrochemical capacitors). Therefore if generated electricity is to be stored, it is changed into another form of energy that is easier to store in larger quantities, for longer times and at lower costs, and then converted back to electricity when required. There is always a round trip efficiency penalty with R-storage devices for electricity, which is determined by the type of technology.

Electrical networks have been in operation since the late 19th century, providing a source of energy that is clean at the point of use and immensely adaptable (Ausubel and Marchetti, 1996). Network operators have always had to balance the difference between network supply and demand within defined limits, in order that equipment connected to the network and the network itself is not damaged.

The UK transmission network operator currently uses many different market based services in order to continually match network supply with demand over differing time periods; mandatory frequency response, firm frequency response, frequency control demand management, fast (spinning) reserve, fast start, demand management, short-term operating reserve (STOR), residual reserve and contingency reserve. For a description of terminology see National Grid's website,[1] and for a further description of terminology and principles of the market operation, see Gross et al. (2007). Dispatchable loads and generators, interconnectors and R-storage can supply a range of these balancing services, but differing technologies will be preferred to provide particular services, determined by both the technologies and economics of providing the service.

Although R-storage capacity has increased alongside the growth of electricity networks, it has done so at a much slower pace than that of generating capacity, as other methods of balancing supply and demand have been favoured. Increasing the effective network size by connecting local networks to form regional networks and then to form national and international networks has allowed for the pooling of response and reserve plant to provide the balancing and ancillary services required to keep the network voltage and frequency within defined limits. Increasing the effective network size not only provides a benefit and greater resilience to the supply side when a portfolio of differing primary energy inputs are used, but also provides a similar aggregated benefit at the demand side as a greater number of users with less than perfectly correlated load profiles are connected to the network.

The network thus benefits from having a portfolio of generation technologies that compete not only in price but also in terms of characteristics, to provide a flexible output to the network. Several technologies are limited in operability either by being non-dispatchable, the rate that they can ramp their output up or down, or their minimal stable generation (MSG). Wind derived generation can be forecast up to a point, but not directly dispatched. Large thermal plants such as coal, nuclear and combined cycle gas turbines take many hours to increase their output from a cold start, as thermal stresses on turbines, pipework and boiler equipment have to be kept within limits. However, dispatchable thermal generators do provide response and reserve services to the network as they can generate at a reduced output (part loading), which enables them to increase or decrease their output, over timeframes appropriate to providing balancing services. Hydro-pumped storage schemes, open cycle gas turbines and diesel generators can increase and decrease their output in minutes rather than hours, and so also provide balancing services to the network. On the demand side, ''Frequency Response by Demand Management'' services allow the network operator to contractually interrupt the supply to certain large electricity users. Dynamic Demand Control (DDC) also aims to provide economic frequency stabilisation and peak shaving through the individual control of many smaller and highly distributed loads e.g. domestic fridges and freezers, and although a very promising addition to network stability, DDC has not been utilised on a significant scale so far (Short et al., 2007). There are thus many alternatives that the network operator can utilise in order to keep the network voltage within defined limits.

The lower cost of providing additional dispatchable generating capacity coupled with an increase in the effective size of electrical

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[1] National Grid's website under UK-electricity-balancing services—http://www.nationalgrid.com/uk/Electricity/Balancing/services/balanceserv/intro/.

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networks and demand management has allowed network operators to balance supply with demand with only relatively small amounts of the higher cost forms of R-storage.

3. Existing storage of the UK electricity network

This section looks at the existing electrical storage of the UK electrical network by examining the F-storage of distributed coal stocks and gas in storage, followed by the R-storage of hydro-pumped storage plants. These fossil-fuel stores give an indication of the orders of magnitude of calorific energy available to be converted into electricity. Oil has not been investigated in this paper due to the difficulty in sourcing data on oil stocks for electricity production. However it is noted that oil fuelled generators provided ~1.4% of the total electricity supplied to the UK grid over the year 2008 (DUKES 5.6, 2009), which is a similar amount provided by hydro-natural flow, and slightly greater than hydro-pumped storage (~1.1%).

The amount of electricity that could be generated from nuclear fuel stocks is not publicly available as stated in the Energy Markets Outlook to parliament, "The stockpiling of fuel in the UK is the responsibility of the utilities concerned and information on the stock levels in the UK is commercially confidential." (EMO, 2009). However, a paper on world nuclear stocks by Maeda et al. (2005) also states about commercial inventories of nuclear fuel—"The analysis we did this time found that the commercial inventory has been almost maintained from the previous report analysis (2003), which is approximately 110,000 tU, 150% of world annual consumption." We therefore feel that the nuclear fuel stocks for UK electricity production can conservatively be estimated at over a year.

The average distributed coal stocks for electricity generators from January 1995 to October 2009 was found to be 12,087,000 tonnes. The stocks ranged between 6,226,000 tonnes in April 1996 to 22,890,000 tonnes in September 2009 (Fig. 1). Combining these data with the monthly data for electricity generators' coal consumption gives an average stock level of ~95 days. This, however, ranged between 29 days in March 1996 and 342 days in August 2009 (monthly coal stocks (DUKES 2.6, 2009) divided by the monthly coal consumption (DUKES 2.5, 2009). There is a considerable seasonal variation of coal stocks, and as the level is not mandated, it is presumed that this variation is caused by the determinants of the optimal level of stocks such as price, expected demands and prices for electricity, the cost of storage and any perceived risks determined by the length and nature of the supply chains.

Taking the average, minimum and maximum figures for coal stocks from above, with an estimated net calorific value (lower heating value) of 24.9 GJ per tonne, equates to a calorific value of approximately 83,600 GWh for the average, 43,000 GWh for the minimum and 158,300 GWh for the maximum level of coal stocks. Making the assumption that the average efficiency of all UK coal plants is ~35.8%, (DUKES 5.10, 2009) gives an F-storage of average UK coal stocks of almost 29,930 GWh before transmission losses.

Another major fuel that provides energy storage to the UK electrical network is natural gas, although the data are not as clear as the data for coal. In the mid-1980s the UK moved away from a depletion policy for exploiting the UK's continental shelf gas resource, which prioritised the rate of extraction in order to lengthen the time period of depletion, to a policy encouraging the market to maximise the development of the gas resource (Stern, 2004). This change of policy, carried forward by successive Governments, had not prioritised gas storage as a key element of the gas supply chain. This problem was however identified, as witnessed in the Ministerial written statement to the House of Commons in May 2006 (UK Secretary of State, 2006), and an increase in the UK gas storage capacity is being developed by the private sector. Investment in import supply capacity e.g. the "Interconnector", "Langeled", South Wales, and "Balgzand Bacton Line" pipelines, and LNG terminals have spread the risk of supply shocks by diversifying supply routes, but, dependent on the contractual arrangements of the supply, may not have contributed to swing capacity, which is currently provided by the depleting UK gas resource (Codognet and Glachant, 2006). Even if gas storage is available on a particular gas network, ownership and access by third parties are key factors in the effective utilisation of a gas storage facility in order to promote a benefit to the market as a whole (Bertoletti et al., 2008).

Fig. 2 shows the current gas storage capacity in the UK of 47,126 GWh (the areas in dark grey at the top of the figure marked as short, medium and long-term storage) is dominated by the Rough storage facility (the UK's only seasonal storage or long-term facility). This has a capacity of 35,530 GWh (3.3 billion cubic metres of natural gas stored at pressures of over 200 bar), but only

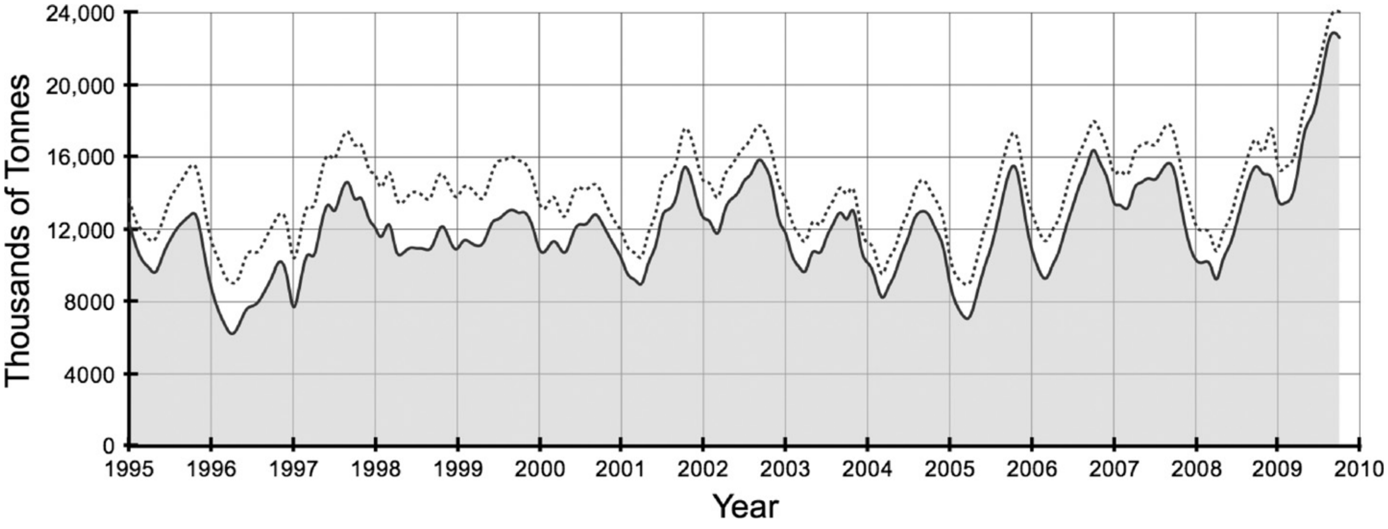

Fig. 1. The variation in UK distributed coal stocks with monthly figures from January 1995 to October 2009. The lines show the variation as stock levels are adjusted throughout the year. The dotted line includes the distributed coal stocks for coke ovens and "other" uses, whereas the series with a continuous line and shading is for electricity generators only. (DUKES 2.6, 2009).

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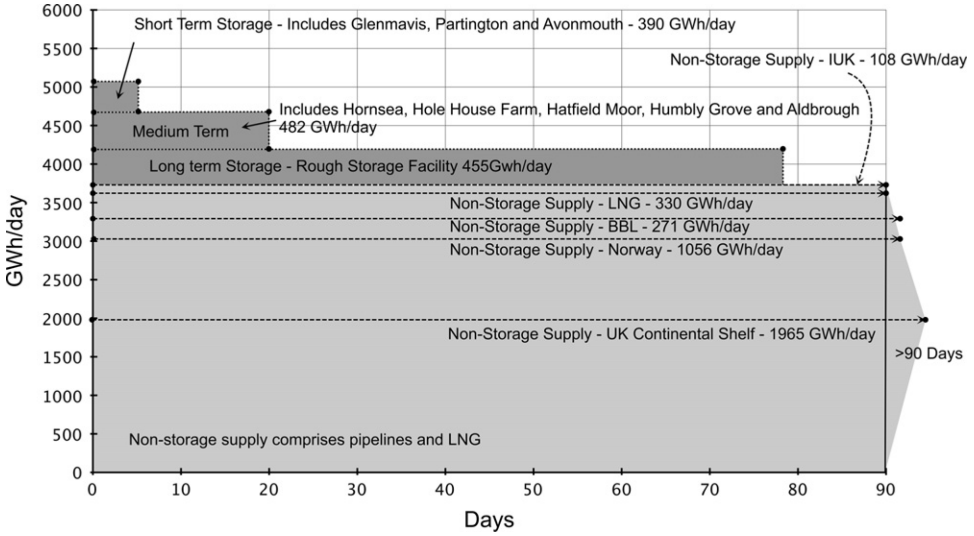

Fig. 2. UK Gas storage and non-storage supply assumptions for winter 2009/10 (NATIONAL GRID, 2009).

Table 1
Hydro-pumped storage schemes in the UK (Mackay, 2009).

Name	Storage capacity (GWh)	Output (MW)	Location	Year of commission
Ffestiniog	~1.3	360	Wales	1963
Ben Cruachan	~10	440	Scotland	1966
Foyers	~6.3	305	Scotland	1974
Dinorwig	~10	1728	Wales	1983

a delivery rate of around 455 GWh (42.4 million cubic metres) of gas per day. By assuming a constant discharge[2] rate this total capacity of 47,126 GWh of gas storage has a maximum delivery rate of 1327 GWh/day for the first 5 days, 937 GWh/day for the next 15 days, and 455 GWh/day for the following 58 days. This is due to the differing capacities and maximum deliverability of the gas storage facilities. For comparison the data for non-storage supply (pipelines and LNG terminals) have been included, which are assumed to provide ongoing capacity in the short term. The capacities will change over the medium term as the contribution from the depleting UK Continental Shelf is reduced. Maximum daily demand for natural gas through the National Transmission System in winter 2007/08 was 4588 GWh on 17 December 2007. These data are taken from National Grid's preliminary safety and firm monitor requirements 2009/10–31 May 2009 (PSFMR, 2009).

In presenting these data from National Grid, the figure does not take into consideration network constraints, the non-linear discharge of the storage facilities, nor storage in the pipelines (line packing). The Fuel Security Code also gives the UK Secretary of State the ability to direct a power station to operate in a certain way, or with a view to achieving specified objectives (FSC, 2007). This ability to divert gas supplies previously available to electricity generation, combined with interruptible supply contracts, means that it is not possible accurately to gauge the amount of gas storage that would be available to electricity generation at times of extremely high gas demand.

Annually, about 30% of gas is consumed in the electricity generating sector, and equally about 30% is consumed in the domestic non-daily metered sector. This paper therefore estimates that 30% of the gas in storage would be used to fuel gas generators in the UK, and that these generators have an overall efficiency of 50%. The F-storage of gas in storage is therefore estimated to be about 7000 GWh. This figure provides an indication of the order of magnitude only, and is not intended as an accurate representation of the actual amount of electricity that could be generated from gas in storage.

Hydro-pumped storage schemes are the largest R-storage schemes within the UK. They have provided a range of balancing and ancillary services to the electrical network for many decades, but as the network has changed over the years, they have been upgraded to allow for many more mode changes than designed at commissioning, and have thus become more flexible. Table 1 details the pumped hydro schemes operational in the UK. The total Hydro-pumped storage capacity is ~27.6 GWh. In 2008 they supplied 4075 GWh of energy from 5371 GWh of input energy used for pumping. (DUKES 5.6, 2009). This equates to an average of 11.13 GWh delivered to the grid on a daily basis (data taken from annual data). This is ~1.1% of the total electricity supplied to the UK grid over the year 2008. This would suggest that the hydro-pumped storage schemes use the majority of their capacity to arbitrage over a daily cycle, in addition to providing ancillary services, by storing (buying) energy at a lower costs and returning (selling) this energy back to the market at a higher cost. In a market based system that does not pay for capacity such as the UK, the price differential has to cover the round trip efficiency losses as well as other costs.

The UK's largest hydro-pumped storage scheme at Dinorwig Power Station in Snowdonia, North Wales has a capacity of ~10 GWh, which equates to the F-storage of approximately 4000 tonnes of distributed coal stocks using a 35.8% efficient coal plant.

The figures for existing distributed coal stocks and gas storage point to electricity storage being overwhelmingly contained within the F-storage in the UK electrical network (36,930 GWh) in comparison to the amount of R-storage (~27.6 GWh). This was

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[2] The discharge of a gas storage facility will not be linear in nature, but a simplified linear approach has been chosen for the purposes of this paper.

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the case within the centrally planned vertically integrated Central Electricity Generating Board (CEGB) before market liberalisation in the UK, and remains the case in the regulated market today. As previously mentioned, the largest point sources of R-storage in the UK are the hydro-pumped storage schemes, whose R-storage capacity is dwarfed by the F-storage by several orders of magnitude, indeed, if the F-storage was to be replaced with R-storage schemes it would require nearly 3700 Dinorwig sized hydro-pumped schemes. The economic and environmental requirements of large energy storage schemes point to the challenge of replacing anything like the existing level of capacity of F-storage with R-storage.

4. Technologies for R-storage (MWh–GWh), and interconnectors

Hydro-pumped storage has been the favoured R-storage technology for the MWh–GWh range throughout the world. The round trip efficiency of hydro-pumped storage is in the region of 70–80% and is viewed as a mature technology for utility level electricity storage, however, it has been restricted to areas with suitable geology and topography. The principle of using the potential energy stored in a body of water is being broadened by proposals such as tidal lagoons, underground reservoirs and large bladders of water covered with layer of sand to provide extra weight.

In comparison to the development of hydro-pumped storage plants, only two Compressed Air Energy Storage (CAES) schemes have provided utility level storage, one in Germany and the other in the US. Both these CAES schemes use natural gas as a fuel, where the cavern provides a store of compressed air in order to increase the efficiency of the gas turbine. The economics of making caverns by solution mining of salt deposits are more favourable than conventional mining, so CAES is also restricted to areas of suitable geology, mainly regions with salt geology, but disused mines have also been investigated to determine their suitability. Adiabatic compressed air energy storage at a large scale still requires significant research, where the heat from compression is stored for later use in expansion of the compressed air.

Generally, these large R-storage schemes have been built to provide a range of balancing and ancillary services to the network e.g. a backup response to a failure of a large generator or electricity line, a black start capacity to allow the restarting of the network after a network failure, reserve provision on a range of timescales, as well as the ability to store and release energy to provide load levelling. As they are still used for these purposes in the UK today, it could be argued that they were a sound long-term investment by the state for the benefit of the network as a whole.

Other methods of providing MWh–GWh of R-storage that have been demonstrated or proposed include: molten salt storage, hydrogen fuel storage, large-scale battery storage, superconducting magnetic energy storage and flow batteries (Kondoh et al., 2000; Hall and Bain, 2008; Mackay, 2007; Ibrahim et al., 2008). Pumped Heat Electricity Storage is also at the early stage of development, but could potentially provide a step change in cost and efficiency without the limitations of geology and topography.

If the above technologies lend themselves to larger point source types of storage then MWh–GWh of R-storage from other forms of smaller scale distributed storage can also be considered. For example, if the UK's 26,508,000 private vehicles[3] each contained rechargeable batteries capable of storing 55 kWh of energy – this would total over 1400 GWh of R-storage – a very significant total amount. Electrification of the private transport sector would obviously be an additional demand on the UK electricity system, with the possible advantage of providing more flexibility to the demand side. However, due to the requirement of private transport vehicles to be charged and available most days, this type of R-storage is less able to provide benefits to the network over weekly or longer timeframes.

The potential for distributed storage at the household level (~26,000,000 UK homes) with similar batteries of 55 kWh could in theory also total over 1400 GWh of R-storage. A similarly significant total amount. Due to the lower power and energy demands of household energy use in comparison to transport, the stored energy could last into the weekly timeframe and so provide additional demand side flexibility over longer timeframes than private transport. This domestic electrical storage could provide an additional benefit within the concept of dynamic demand control as presented by Short et al. (2007) and Infield et al. (2007).

Interconnectors can also provide flexibility to networks by increasing the effective network size as discussed earlier, by allowing the import and export of electricity. These electricity flows are mainly driven by price differentials between the connected markets. Currently there is 2500 MW of High Voltage Direct Current (HVDC) electrical interconnection from mainland UK, 2000 MW to France and 500 MW to Northern Ireland. Although electricity can flow in both directions, energy flows have mostly been inward through the French connection, and outward through the Moyle (NI) connection. Several more interconnectors are at various stages of proposal and deployment as shown in Table 2.

If the capacity of interconnectors to mainland Europe is increased to 3800 MW it should increase the resilience of the UK's domestic system, but this is dependent on the generation plant of the connected grid. By connecting to a network that has a differing mix of energy inputs e.g. a greater reliance on nuclear energy in France, would provide an increased resilience with respect to fuel supply shocks. HVDC interconnectors are capital-intensive projects (Bahrman and Johnson, 2007), and it is presumed that the owners will try to achieve the highest possible load factor of utilisation, especially when connected to the UK market that no longer pays operators for capacity. Interconnectors may or may not be able to play a major role in balancing and ancillary markets, it will depend on the flexibility of technologies and market structures at both ends, and the type of contracted capacity of the interconnector. For example, if the majority of the contracts to use the capacity of an interconnector are subject to longer-term baseload type contracts, then there is less scope for using it to provide short-term increases or decreases to balance the grid.

Table 2
The capacity of UK electrical interconnectors.

Name	Capacity (MW)	Status
UK–France (HVDC Cross Channel)	2000	Operational
GB–Northern Ireland (Moyle); Northern Ireland–Ireland	500, 600 MW	Operational
UK–Netherlands	1000	Under construction—operational
UK–France	800	Under development
UK–Ireland	350	Under development
UK–Ireland	500	Under development
UK–Norway	1200	Proposed

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[3] Department of Transport Statistics 2006—Motor vehicles licensed at end of year. http://www.dft.gov.uk/pgr/statistics/datatablespublications/tsgb/edition20071.pdf pp 158.

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5. Is it necessary to replace F-storage with R-storage?

Even though replacing F-storage with R-storage on a similar scale would be environmentally as well as financially unacceptable, an increase in R-storage can be examined.

Fossil-fuels are energy dense, cost effective stores of energy, but their major drawbacks in terms of UK energy policy include the greenhouse gas emissions from combustion, and an increasing future reliance on imported fuels, as the indigenous production of fossil-fuels reduces. Also, given the supply of fossil-fuels is finite; they are ultimately likely to become more expensive, and therefore less attractive as stores of energy. The UK has set long-term targets of an 80% reduction in CO_2 emissions by 2050 (below 1990 levels), and a 26% reduction by 2020. The 2020 target is expected to require 35% of electricity to be provided by renewable generators. This target is set against the findings of the European power plant database (Kjarstad and Johnsson, 2007) that provides a snapshot of current plant, plant in construction, and planned generation plants in the UK as of May 2006. This paper notes that “70% of the planned capacity is natural gas combined cycles (14 GW gas versus 20 GW in total), although the actual commissioning of some of these plants is highly uncertain. Moreover, 85% of all coal plants are older than 30 years, indicating that natural gas will become even more dominant if the current trend remains”. If this current trend of investing in natural gas plants continues as the UK’s indigenous oil and gas reserves deplete, the UK will become more heavily dependent on fossil-fuel imports, which has implications for energy security for the UK. However, there are a range of opinions regarding the change of risks from increased fuel importation, the paper by Grubb et al. (2006) states that “The major interruptions of the UK energy system in the past three decades have arisen from miners’ strikes, domestic fuel blockades, and occasional power cuts rather than from foreign supply dependence.” The paper also discusses diversification of fuel types and technologies, including the diverse nature of energy inputs into differing renewable energy technologies, as a method to increase the resilience of the network to fuel supply shocks. Nevertheless a scenario analysis published by Bhattacharyya (2009)) indicates that the “UK is likely to face greater gas vulnerability in the future due to increased gas dependence in electricity generation and higher import dependence.” We believe this remains a significant problem for UK energy policy.

The view of whether increased amounts of R-storage would be an advantage to the network is dependent on the future UK energy generating mix, its interconnectivity with larger European grids, the future load profile of the UK, and the legislative status of renewables. These are all largely unknown at this point in time—but the benefit of R-storage to differing generating technologies can be considered. At some future increased level of non-dispatchable renewable energy capacity, it is likely that supply will be greater than demand in certain periods. The options of dealing with this excess supply are to increase the demand to meet supply, to spill (reduce) the excess supply, or to store the excess energy. Unless the excess supply is reduced, demand side management and R-storage are the only methods to deal with this problem, as F-storage cannot utilise the excess supply.

Dinorwig hydro-pumped storage plant (~10 GWh) was initially built when the nuclear build program was expected to increase through the 1970s and 1980s. The increased electricity demand that was forecast did not materialise and the expected nuclear build program was scaled back. Dinorwig was built to provide a balancing service in the event of the output from a large power station being curtailed at short notice and to provide an R-storage scheme in order to store off-peak electricity, which allowed baseload generators (nuclear) to remain more efficient by keeping a steady state output matched to their highest efficiencies. There is some hope that the 3rd generation of nuclear power plants will have an increased operability in order to load follow (Hore-Lacy and Cutler, 2009). But if future nuclear plants are utilised as inflexibly as historical plants, then R-storage offers a method to increase the system flexibility.

Significant research effort is being devoted to the development and deployment of carbon capture and storage (CCS) for fossil-fuel generating technologies. Dependent on the technology and design of the plant, post-combustion CCS plants can be designed to quickly reduce the steam requirements for the carbon capture process, which would have the effect of providing a reserve output to the grid, albeit at the expense of increased carbon emissions for periods of time. Large amounts of R-storage are unlikely to be beneficial to fossil-fuel plants with CCS, if their operability is equal to or even enhanced from the current generation of fossil-fuelled plants, indeed, “In the medium to long term it seems likely that flexible operation of most or all fossil plants could become virtually obligatory in many plausible lower carbon electricity generation mixes in many jurisdictions” (Chalmers et al., 2009). An overview of the technologies, and likely benefits and disadvantages to operability of coal-fired plants with CCS is provided by Chalmers et al. (2006, 2009), Chalmers and Gibbins (2007). The best route for policy makers to encourage this flexibility in CCS generation is unclear and also requires consideration, but if CCS allows the continued use of F-storage, then it is critical that greater flexibility is designed from the outset.

A large increase in wind generation is planned in the UK; the eventual amount is unclear but if the 2020 target is expected to require 35% of electricity to be provided by renewable generators the increase will be significant. The combination of variable generation and R-storage can provide a higher degree of certainty to the predicted output from their combined output. The market structure in the UK requires electrical generators to offer figures for the price and power they are able to supply to the network. Every 24-h period is divided into 48 rolling half hour blocks that generators can potentially aim to supply, with the closing gate for bids being 60 min before the time period in question. If generators are not able to provide the predicted level of output for the timeframe 60 min in the future, they will suffer financial penalties. Wind farm operators thus have to predict the available output from their wind turbines for the half hour block starting in 60 min time. R-storage allows the wind farm operator the ability to balance a predicted output (in 60 min) and thus reduce the amount of financial penalties. The amount of R-storage can be optimised for a given timeframe, i.e. a 30-min timeframe will require less storage than a 120-min timeframe, and are likely to be of the MWh scale. A paper by Bathurst and Strbac (2003) describes an algorithm to maximise value added with this type of R-Storage. In a paper by Apt (2007) the power spectral density of the output of wind turbines was analysed using real data over a period from 2001 to 2004. The output was shown to follow an $f^{-2/3}$ Kolmogorov spectrum over the frequency range 30 s–2.6 days. A conclusion was that any “fill-in” power to compensate for the variable output of wind generators should have the ability to fluctuate its output in a similar manner. Linear generators such as a gas generator follow a Kolmogorov spectrum with a different value. It was concluded that the combination of differing storage technologies (fuel cells, batteries, electrochemical capacitors, and F-storage) would be better able to provide the “fill-in” power.

It should be borne in mind that as the size and topology of the network have a large influence on the benefit R-storage systems could provide (Lund and Paatero, 2006), that different parts of the network will undoubtedly require different solutions. Large-scale

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R-storage has been discussed as a backup for wind generation on a weekly scale (as weather patterns with low wind speeds can dominate over weekly rather than daily periods), which would require R-storage in the 100s of GWh–TWh range rather than the GWh range as exists now. This level of R-storage would be required if F-storage is not available, perhaps because of limited CCS deployment.

The scale of present-day stocks of fossil-fuels is heavily influenced by the length and nature of their supply chains, coupled with their variability in price. It can be argued that a move towards renewable energy generators removes or reduces the price variability of energy inputs, and also changes the risks associated from long supply chains to the risks associated with the variability of the weather. If the current combined level of F-storage and R-storage is adequate due to the framework of fossil-fuel supply chains, it is thought that the differing renewable energy supply chains (e.g. wind, solar, tidal, wave and biomass) would require reduced levels of combined storage. As previously mentioned, the level of combined storage required will be influenced by many variables, not only the nature of the energy inputs (fuels or renewable energy), but also the type of generators, the type and level of balancing and ancillary services to be provided, the demand profiles, and the network topography. As a multi variant problem at a network level, it is complex to determine what an appropriate level of combined storage would be for a particular future UK network. Complex modelling using a combination of WASP, CGEN and MARKAL models can provide an ability to test various scenarios, giving valuable knowledge to policy makers (UKERC, 2009). If the variables are reduced to the level of individual generators (e.g. wind farms or even wind turbines), with known network constraints, statistical patterns of supply and demand, and well-understood market price variables, there is the potential to undertake an investment appraisal with these reduced set of variables for this distinct part of the network. This is indeed happening, and has provided the rationale behind private sector investments in R-storage not only in the UK but also around the world.

If policy makers decided that large-scale network R-storage was to be encouraged within the market framework in order to promote a greater benefit to the market as a whole, then consideration should be given to ownership and access by third parties. It should be noted that even though all the hydro-pumped storage schemes were built by the vertically integrated state-owned network operator before market liberalisation, that upgrading and a ~10% increase in the capacity of Dinorwig has taken place under regulated market conditions. The existing hydro-pumped storage schemes are thus under private ownership, with no access rights for third parties, and do provide a benefit to the market as a whole in terms of load levelling and ancillary services.

If CCS can provide low-carbon use of the calorific energy contained in fossil-fuel stores, in the short to medium term it may not be strictly necessary to replace F-storage with greater levels of R-storage, but it would be wise to use this time period to explore other forms of R-storage, and to increase market knowledge and participation before it does indeed become essential to replace F-storage in the future. It is difficult to imagine TWhours of R-storage being built in the UK's liberalised electricity market for weekly storage of renewable energy if dispatchable low-carbon generating technologies can continue to use F-storage. It is assumed that in the future UK liberalised electricity market there will still be a finite limit to the amount and types of balancing and ancillary services required, and if these are secured by low-carbon generating technologies using F-storage, that there will be little requirement for further large-scale R-storage schemes to be built. However, due to the expected increase of non-dispatchable generating plant, there should also be an increased requirement for more R-storage in order to overcome local network constraints, provide additional balancing services, and provide increased network flexibility and resilience.

6. Conclusions

Storage has always been a key element of electrical networks that has historically been dominated by F-storage. The decarbonisation challenge facing the UK electricity sector should be viewed not only as a supply and demand challenge, but also as a storage challenge. As the percentage of non-dispatchable low-carbon generators increases in the future UK electrical generating mix, the importance of flexible generation technologies and flexible demand side strategies to balance the network will increase in importance. In particular, the problem of excess supply looms large, which requires an R-storage solution or flexibility to increase demand. R-storage offers benefits to both the supply side and the demand side of the network, the challenge lies in determining the best type, location and scale of this storage. It is thought that the reasons for the large amounts of existent F-storage are due to the inherent risks associated with long supply chains and price volatility. When the system eventually changes to a system whose primary energy is based on, to a much greater extent, indigenous renewable sources with much shorter supply chains and less (or no) price volatility for the fuel, then the total amount of energy contained within combined F-storage and R-storage can be reduced, as the risks will change from the risks inherent in long supply chains to the risks associated with renewable energy resources.

However, due to the present mix of F-storage and R-storage on the UK network (over 99.92% F-storage vs. under 0.08% R-storage), combined levels of storage are likely to continue to be dominated by F-storage for the short to medium term, with the hope that carbon abatement technology and strategies can be scaled up to reduce the greenhouse gas emissions from their continued use. The challenge for new power plants that use fossil-fuels with CCS or nuclear fuel is to have an increased operability that will allow must-run renewable generating plant to supply low-carbon electricity when available.

R-storage at the small and medium scale (kWh–MWh) will be a key enabling technology to allow demand side strategies to be even more flexible, as well as providing increased resilience throughout the network. In a future world that has greater volatility in fossil-fuel prices, the development of economic fuels that can be manufactured using excess energy, or other forms of large-scale R-storage that are less dependent on the difficulties posed by geology and topography, would provide a potential to provide seasonal storage without F-storage, and thus provide a hedge against price volatility of fossil-fuels. Given uncertainties about the flexibility of operation of future CCS and nuclear plants, concerns about security of supply of both nuclear and fossil-fuels, the obvious current dominance of F-storage within the network, increased price movements, and the possibility of synergy between the electrical network and the transport network it would be judicious for policy makers to give serious consideration to the potential role for significantly increased levels of R-storage.

Hall and Bain (2008) have drawn attention to the large diversity of energy storage technologies available and their associated major technical challenges, whereas this paper has drawn attention to the scale of energy storage that exists on the UK network. However, in addition to these major technical challenges, serious questions have not been addressed such as: the amount and location of where energy storage should be incorporated into energy transmission and distribution grids; the

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balance between different energy storage technologies; the importance of charge/discharge efficiency and indeed how a greater market for energy storage could be developed.

Increased research and development funding should be focused not only at the large-scale level, but also at the distributed level, as modular R-storage in the 10–100 kWh range could not only benefit distributed storage and domestic demand side strategies, but also meet the R-storage requirements of passenger vehicles. The continuing research and development of R-storage technologies in this range would therefore not only help with building a resilient distributed R-storage capacity through vehicle to grid and home to grid applications, but would also help the aim of decarbonising transport using electric vehicles.

Research into heat storage for space heating/cooling and hot water requirements is also a hugely important area (although not discussed in this paper). Further exploration of the costs and benefits of various R-storage technologies, with a greater understanding of the societal costs and benefits would allow a fuller understanding of policy options. A comprehensive study of the barriers to increased R-storage within the UK is also required (which should include regulatory and market barriers as well as technology barriers), in order to speed up the deployment of R-storage.

It is our belief that in the long-term, the UK will eventually evolve away from fossil-fuels for its main primary energy source. However, for this to happen, R-storage capacity will have to be radically increased.

Acknowledgements

This work was supported by the EPSRC Supergen Energy Storage programme under grant reference EP/D031672/1, and by the EPSRC Supergen Marine Consortium under grant reference EP/E040136/1.

We are also indebted to the three reviewers for their helpful and insightful comments.

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