

Literature Review: Electrical Energy Storage for Scotland

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Executive Summary

This report examines the role and value of energy storage in the context of electricity systems that are expected to absorb increasing quantities of time variable electricity generation from renewable sources in the years ahead. Particular attention is given to Scotland with its vast renewable energy potential and limited interconnection to the parts of the UK with the major electricity loads. Energy storage technologies cover a wide range of levels of development from mature technologies like pumped hydro with over 50 years of operational experience, to technologies still under development such as flow batteries and hydrogen storage systems, and all of these are reviewed. All scales of possible application are considered here from whole power system support, through community power provision, down to individual households.

Energy storage has the potential to contribute to the operation of power systems in a number of ways. The most important are:

1. Managing intermittency caused by the integration of time variable renewable sources of generation, and thereby facilitating improved decarbonisation of the electricity supply system.
2. Providing solutions in grid constrained areas.
3. Supporting energy security.
4. Operational cost savings and financial/commercial opportunities.

An obvious alternative to energy storage is improved electricity transmission and distribution; this is especially clear in the case of the north-south interconnector and future investments in this and its impact are addressed in this review.

The following table provides a summary of the key electrical energy storage technologies and their various attributes.

Literature Review: Electrical Energy Storage for Scotland

Technology	Description	Power (MW)	Capacity (MWh)	Duration of power	Benefits	Limitations	Lifetime	Applications	Comment
Pumped Hydro	Water is pumped to a higher level off-peak, then flow is used to release stored potential energy in response to demand	280 – 14000	1680 – 14000	<10 hrs	<ul style="list-style-type: none"> • Mature technology • Reduces peak loads • 75-80% efficiency • Low operation & maintenance costs 	<ul style="list-style-type: none"> • Capital costs • Site selection 	>13,000 cycles	<ul style="list-style-type: none"> • Load management • Inter-seasonal storage 	Mature technology 2 sites currently in Scotland – Cruachan (400MW) & Foyers (300MW)
Pumped hydro (seawater)	Lower reservoir is seawater	30	Not known	Not known	<ul style="list-style-type: none"> • Site flexibility 	<ul style="list-style-type: none"> • Increased capital costs (corrosion resistance) • Immature technology 	Not specified	<ul style="list-style-type: none"> • Load management • Inter-seasonal storage 	30MW unit has been installed in Japan
Pumped hydro (underground reservoir)	Caverns or abandoned mines are used for lower reservoir	Not known	Not known	Not known	<ul style="list-style-type: none"> • Reduced environmental impact 	<ul style="list-style-type: none"> • Location specific • Immature technology - Speculative 	Not specified	<ul style="list-style-type: none"> • Load management • Inter-seasonal storage 	No existing or planned unit identified
Compressed Air Energy Storage	Stores energy (generally in underground caverns) as compressed air during low cost/ low demand times; when required, air is combined with hydrogen or natural gas & passed through combustion turbine	10 - 400	1440 – 3600	5 - 30 hrs	<ul style="list-style-type: none"> • Mature technology • Reduces peak loads • 73-89% efficiency • Integrates well with wind generation systems • Low operation & maintenance costs 	<ul style="list-style-type: none"> • Capital costs • Site selection (safety risks & suitability for high pressure storage) • No suitable sites yet identified in Scotland 	>10,000	<ul style="list-style-type: none"> • Load management • Inter-seasonal storage 	Few active demonstration sites, examples include Huntorf (Germany) & McIntosh (Alabama, USA)
Flywheels	Kinetic energy stored by driving a motor that will spin a mass & discharged through the spinning mass driving a motor generator to produce electricity	20	5	0.25 hrs	<ul style="list-style-type: none"> • Mature technology • Easy to site • 70-80% efficiency 	<ul style="list-style-type: none"> • Structural deficiencies pose a safety risk • noise 	>100,000	<ul style="list-style-type: none"> • maintaining power quality or reliability 	Technology under further development

Literature Review: Electrical Energy Storage for Scotland

Technology	Description	Power (MW)	Capacity (MWh)	Duration of power	Benefits	Limitations	Lifetime	Applications	Comment
Electrical/ Battery storage	Stores electrical energy within a chemical medium – electrical batteries involve the flow of electrons between the anode and the cathode of the battery.	1 - 100	4 - 400	0 - 7hrs	<ul style="list-style-type: none"> • Ability to quickly switch modes of operation to charging and discharging • Site flexibility • Maturity of technology - varies from mature technologies such as Lead acid to batteries that are only available in demonstration projects 	<ul style="list-style-type: none"> • Size of battery • Shorter lifetime (depends on chemistries) • Significant environmental impact in manufacture; • Location near sub-stations problematic 	2200 - >100,000 cycles	<ul style="list-style-type: none"> • Potential for power quality management • Load management 	There are many types of battery that are suited to different uses, these are discussed further in the report.
Flow batteries	Fluid in the cells is stored separately and pumped during charge & discharge for the chemical reaction; include hybrid flow & redox flow batteries	1 - 50	4 - 250	4 - 5 hrs	<ul style="list-style-type: none"> • Can be scaled up – capacity depends on storage tanks for fluid 	<ul style="list-style-type: none"> • Significant space requirement • Capacity dependent on volume of electrolyte • High maintenance requirement • Can have lower efficiency 	10,000 cycles	<ul style="list-style-type: none"> • Potential for power quality management • Load management 	Technology still under development
Hydrogen	Water is converted by electrolysis into its constituent elements (hydrogen & oxygen) and reconverted to electricity using fuel cells, or used as fuel (eg added to gas distribution system)	Not known	Not known	Not known	<ul style="list-style-type: none"> • Versatile – uses include electricity generation, heating, cooking and transport, • Lower environmental Impact • Potential for generating hydrogen from surplus electricity 	<ul style="list-style-type: none"> • Need for hard data • High cost • Uncertain performance • Health & safety concerns 	Thousands of cycles	Load management	<p>Option to generate hydrogen from surplus electricity to add to the gas distribution system, storing some hydrogen in the gas system.</p> <p>Unst and Aberdeen are progressing Hydrogen projects</p>

Technology	Description	Power (MW)	Capacity (MWh)	Duration of power	Benefits	Limitations	Lifetime	Applications	Comment
Super/Ultra capacitors	Store electrical energy within an electric field; storage capacity of the capacitors is determined by the surface area of the conducting plates	Not specified	Not specified	Seconds	<ul style="list-style-type: none"> • Longer lifespan than conventional batteries 	<ul style="list-style-type: none"> • Failure of one unit compromises full system • Careful siting required • Fire risk • Ultra-capacitors can't be recycled 	Not specified	<ul style="list-style-type: none"> • Power quality management 	Expensive and to date only considered for specialist applications such as meeting peak demands from electric vehicles
Superconducting magnetic energy storage	Stores energy in a magnetic field generated within a superconducting coil. The coil is then discharged to release the energy	Not specified	Not specified	Seconds	<ul style="list-style-type: none"> • Highly efficient • Swift reaction when required 	<ul style="list-style-type: none"> • Requires refrigeration system which also requires 	Not specified	<ul style="list-style-type: none"> • Power quality management 	Very few applications such as stabilization of long transmission lines
Thermal storage of electrical energy as heat to be used as heat (for example in district heating systems, or in homes). New proposed technology for electrical reconversion using heat engines	Electricity can be used to generate heat that is then stored either in water tanks which are connected to a district heating system or in storage heaters in consumer's properties.	Not specified	Not specified	Hours to days	<ul style="list-style-type: none"> • High power ratings and high energy ratings. • Relatively simple to add storage capacity 	<ul style="list-style-type: none"> • Few district heating systems in Scotland • Storage in individual properties could require significant heating system upgrades. 	Not specified	<ul style="list-style-type: none"> • Load management 	Heat storage is mature and widely used for supplying heat loads. Reconversion to electricity requires very high storage temperatures and is unproven.

Table 1 – Electrical Energy Storage Technologies: Summary Comparative Analysis

1. Introduction

The Scottish Government is committed to a low carbon economy and has set legislative targets of generating at least 30% of our energy needs from renewable sources by 2020, and an overall reduction in greenhouse gas emissions of 80% by 2050. Energy storage has the potential to improve security and reliability of supply, in order to meet both current and anticipated energy demands both within and beyond the current national grid system.

1.1 Objective

The Scottish Government commissioned this literature review to understand the potential and limitations of energy storage across the electricity sector, and touching on heat and transport where relevant. This report reviews the current literature on energy storage, considering in particular issues around integration of renewables in the grid. The focus is largely on Scotland, although reference to evidence from other countries is made where relevant.

1.2 Background

The Scottish Government's Electricity Generation Policy Statement states that electricity storage could play an important and growing role alongside renewable electricity production, helping to address the intermittency of certain forms of renewable generation, complementing interconnection and demand-side response¹.

Box 1 – Potential Benefits of Increased Use of Storage

- allowing the best use of existing generation and in particular renewable energy resources;
- scope for using electricity generation to support clean fuel development for transport and heat;
- reduced reliance on fossil fuel stations as back-up capacity;
- helping to stabilise the transmission and distribution grid – using stored energy to avoid temporary constraints on the network and to improve power quality;
- benefits for generators who could store electricity when prices are low and sell it when prices are high;
- potential savings in greenhouse gas emissions; and
- the potential for storage to provide 'black start' capacity.

Source: Scottish Government Electricity Generation Policy Statement

¹ Electricity Generation Policy Statement, [Scottish Government, 2013](#)

As renewable energy penetration continues to rise in the GB power system, it is essential that we understand how this might impact upon the management of energy flows in response to variable demand and supply. For electricity, peaks in demand have traditionally been handled by increasing generation from fossil fuels. However, this approach may not be best suited to managing a system with significant renewable penetration. Renewable electricity technologies that are currently in use and commercially viable are less able to respond to changes in demand than conventional plant. Energy storage, as in effect an additional source of power generation, has the potential to enhance security and reliability of supply, helping to meet both current and anticipated energy demands.

The Scottish Government has set a target of 500 MW of community and locally-owned renewables by 2020. The Scottish Government also has declared its ambition to see the development of a localised, robust, more distributed energy system to meet Scotland's energy needs². In the context of local energy supply from renewable generation, energy storage can be used to absorb local surplus that cannot be exported due to connection constraints, allowing this surplus to be used later to meet local demand.

While the government is implementing policies for energy demand reduction, related efforts to cut fossil fuel use, in particular the projected significant increased uptake of electric vehicles (EVs) will result in a corresponding increase in demand for electricity. Such changes bring into sharp focus the potential for incorporating energy storage into existing power systems.

The following topics are addressed in this report. First, a short summary of the literature is presented. This is followed by a brief examination of Scotland's current and future electricity system. Scotland is part of the GB electricity system and particular issues concerning the interconnector to England will be touched on. This is followed by a review of the uses of electricity storage technologies, including their ability to add value to the operation of the power system as a whole. Finally, some conclusions based on the review are drawn, including a sketch of some possible alternative strategies for accommodating very high penetrations of renewable energy into power systems, with particular reference to GB. The appendix provides a side-by-side comparison of the most promising technologies and the practical opportunities and challenges that arise with installation and operation. Practical issues and in particular any barriers to the installation of storage options are presented.

² Community Energy Policy Statement, [Scottish Government, 2014](#)

2. The Literature

The energy storage literature is extensive, and many papers and reports have been accessed to provide the background to this review. These fall into three broad categories:

- Syntheses commissioned by government or professional and industry bodies
- Academic papers reporting on research into the effectiveness of the available technologies
- In-depth analyses of the economic costs and benefits

Much of the literature is detailed and technology specific, focusing on the effectiveness of the technology. An up to date and comprehensive review of technologies is available from Purdue University³, and this is used extensively in this review.

Overall, there is a lack of literature that critically assesses costs or provides robust analysis of the economic value that could be delivered in a system context. In its recent review of energy storage, the Institute of Mechanical Engineers (IMechE)⁴ presented a useful table of costs drawn from other studies (see Table 3) However, this highlights the uncertainties in costs, even for well-developed technologies. The International Energy Agency (IEA) Technology Roadmap – Energy Storage⁵, provides international context and highlights existing market constraints as a key issue limiting the potential economic value of electricity storage in the sense that the market does not presently allow the full value of energy storage to be realised. Similarly, a 2010 study for the Scottish Government concluded that, **at least with the current existing market and regulatory framework**, storage was not economic in comparison with alternatives such as constraining generation, or investment in greater interconnection⁶.

There are a few key recent sources that provide a useful starting point relevant to storage in the Scottish electricity context. This review found that the most relevant of these are power system studies^{7,8} and in particular those that examined power flows across the border between Scotland and England.

The following table provides a summary of the key literature used to provide background, analysis and illustrations for this report. Additional, but less central literature, is referenced in the remaining text.

³ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report form State Utility Forecasting Group, University of Purdue, June, 2013

⁴ Energy Storage: The missing link in the UK's energy commitments; Institute of Mechanical Engineers, 2014.

⁵ International Energy Agency, "Technology Roadmap: Energy Storage," 2014

⁶ Energy Storage and Management Study; 2010 report by AEA

⁷ Scottish Generation Scenarios and Power Flows: An Analysis, Sinclair Knight Merz, 2011.

⁸ Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future; Report for the Carbon Trust by the Energy Futures Laboratory, Imperial College, June 2012

Literature Review: Electrical Energy Storage for Scotland

Source	Brief overview	Limitations and evidence gaps highlighted
R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report from State Utility Forecasting Group, University of Purdue, June, 2013	Useful introduction to energy storage; detail on each storage approach, with clear introduction on how it works and a useful breakdown of strengths and weaknesses. Only pumped hydro and selected battery technologies (lead acid, sodium sulphur, and lithium-ion) are identified as mature, with the remainder somewhere between research and early deployment. Storage costs, and operational value in the context of the US power system are summarised, but the report indicates that such figures should be treated with caution.	Conclusions with regard to economic value of energy storage are specific to US power system.
Energy Storage: The missing link in the UK's energy commitments; Institute of Mechanical Engineers, 2014	Useful, recent literature review by the Institute.	Useful consideration of costs, but incomplete, so some caution required.
Scottish Generation Scenarios and Power Flows: An Analysis, Sinclair Knight Merz, 2011	Report commissioned by the Scottish Government to examine two alternative scenarios that meet renewable ambitions. Demonstrates how energy storage might fit into the energy system.	Opportunities and challenges not addressed.
Technology Roadmap: Energy Storage; Report by the International Energy Agency, 2014	A comprehensive report considering both the current state of the technologies, their potential in the medium term future and the policy and market context.	
Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future; Report for the Carbon Trust by the Energy Futures Laboratory, Imperial College, 2012	Takes a comprehensive whole systems analysis approach to establish the role and quantify the value of electricity storage, alongside alternative technologies. Includes a brief summary of the technologies.	Little coverage of issues around future potential.
Energy Storage and Management Study; AEA, 2010	Commissioned by the Scottish Government to gain insight into the comparative roles of energy storage, demand side management technologies and transmission reinforcement.	May require updating in light of Electricity Market Reform and other changes.
State of Charge of GB; Report by the Energy Storage Operator's Forum, 2013	2 page report with a table of UK installations; includes Scottish sites on Orkney, Shetland and Nairn and brief sections on benefits realised and knowledge sharing.	No technical details.

Table 2 - Summary of key literature sources reviewed

The following sections, 2.1 and 2.2 provide a short summary of what the literature reviewed says about storage costs and benefits.

2.1 Electricity Storage Costs and Benefits

This section brings together results from various studies so that the different costs and capabilities of storage technologies can be reviewed and compared.

Cost Comparison of different Energy Storage Technologies	Carbon Trust ^[17]		CLCF ^[10]	
	Indicative Cost		Indicative Cost	
	US\$ / kW	US\$ / kWh	US\$ / kW	US\$ / kWh
PHES	1500–4300	250–430	600–2000	5–100
CAES – underground	1000–1250	60–125	400–1150	2–120
CAES – above ground	1950–2150	390–430		
CES	n/a	n/a	900–2000	260–530
Hydrogen	n/a	n/a	1500–10000	6–725
Flywheel	1950–2200	7800–8800	250–25000	1000–14000
Batteries:				
Redox flow – Zn/Br	1450–2015	290–1350	600–2500	150–1000
Redox flow – V/V	3000–3700	620–830		
Lithium-based	1085–4100	900–6200	400–1600	600–3800
Metal-Air	n/a	n/a	100–1700	10–340
Sodium-based	3100–4000	445–555	350–3000	300–500
Nickel-based	n/a	n/a	400–2400	800–1500
Advanced Lead Acid	950–4600	625–3800	n/a	n/a
Lead Acid	n/a	n/a	50–600	200–400
SMES	n/a	n/a	200–350	1000–10000
Supercapacitor	n/a	n/a	25–510	300–20000

Table 3: Summary of energy storage costs taken from IMechE 2014 report.

Table 3⁹ highlights the large uncertainties in costs of the different storage technologies.

Table 4 is based on information in an Electric Power Research Institute (EPRI) report from 2010¹⁰. The indications of cost are highly conjectural and the uses noted for each application are not comprehensive. The table is therefore intended to act as a preliminary guide to the available technologies' characteristics and maturity. Note that those figures in Table 3 referenced *Carbon Trust* are taken from Table 66 of the Imperial College report for the Carbon Trust¹¹, which are taken unchanged from the EPRI 2010 report.

⁹ Energy Storage: The missing link in the UK's energy commitments; Institute of Mechanical Engineers, 2014.

¹⁰ Electricity Energy Storage Technology Options, A White Paper Primer on Applications, Costs, and Benefits; EPRI report 1020676, 2010.

¹¹ Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future; Report for the Carbon Trust by the Energy Futures Laboratory, Imperial College, June 2012.

Technology Option	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	% Efficiency	Total Cost	Cost (\$/kWh)
Bulk Energy Storage to Support System and Renewables Integration							
Pumped Hydro	Mature	1680-14000	280-1400	6-10	80-82 (>13,000)	1500-4300	250-430
Compressed Air (underground)	Commercial	1080-2700	135-180	8 - 20	See note 1 (>13,000)	960 -1250	60 -125
Sodium-Sulfur	Commercial	300	50	6	75 (4500)	3100-3300	520-550
Advanced Lead-Acid Battery	Commercial	200	50	4	85-90 (2200)	1700-1900	425-475
	Commercial	250	20-50	5	85-90 (4500)	4600-4900	920-980
	Demo	400	100	4	85-90 (4500)	2700	675
Vanadium Redox	Demo	250	50	5	65-75 (>10000)	3100-3700	620-740
Zn/Br Redox Battery	Demo	250	50	5	60 (>10000)	1450-1750	290-350
Fe/Cr Redox Battery	R&D	250	50	5	75 (>10000)	1800-1900	360-380
Zn/air Redox Battery	R&D	250	50	5	75 (>10000)	1440-1700	290-340
Energy Storage for Utility Transmission & Distribution Grid Support Applications							
Compressed Air (aboveground)	Demo	250	50	5	See note 1 (>10,000)	1950-2150	390-430
Advanced Lead-Acid Battery	Demo	3.2-48	1-12	3.2-4	75-90 (4500)	2000-4600	625-1150
Sodium-Sulfur Battery	Commercial	7.2	1	7.2	75 (4500)	3200-4000	445-555
Zn/Br Flow	Demo	5-50	1-10	5	60-65 (>10,000)	1670-2015	340-1350
Vanadium Redox Battery	Demo	4-40	1-10	4	65-70 (>10,000)	3000-3310	750-830
Fe/Cr Flow Battery	R&D	4	1	4	75 (>10000)	1200-1600	300-400
Zn/air Battery	R&D	5.4	1	5.4	75 (4500)	1750-1900	325-350
Li-ion Battery	Demo	4-24	1-10	2-4	90-94 (4500)	1800-4100	900-1700
Energy Storage for Frequency Regulation and Renewables Integration							
Flywheel	Demo	5	20	0.25	85-87 (>100,000)	1950-2200	7800-8800
Li-ion Battery	Demo	0.25-25	1-100	0.25-1	87-92 (>100,000)	1085-1550	4340-6200
Advanced Lead-Acid Battery	Demo	0.25-50	1-100	0.25-1	75-90 (>100,000)	950-1590	2770-3800

Table 4: Energy Storage Characteristics by Application

The costs for pumped hydro systems (PHES in Table 3) are highly site-dependent. SSE has made a detailed assessment of 2 potential sites in Scotland, and while the specific cost projections have not been disclosed, the fact that neither of the proposals has yet been progressed suggests that challenges remain in realising the potential of this technology at present. SSE initially explored further sites, but these have not been pursued.

In addition to the financial cost of construction and maintenance, effort is required to ensure that the plant is designed to minimize the environmental and social impact. As suitable sites are frequently geographically remote, additional dedicated transmission lines would be required to link them to the power system. Overhead lines in such locations are likely to be controversial, while buried cables would add substantially to the cost.

Underground compressed air storage (CAES underground) is also highly site dependent.

Other electricity storage technologies are better suited to smaller modular systems for distributed generation, rather than bulk or centralised storage. These conclusions are confirmed by AEA’s 2010 study¹² which ranked the different energy storage technologies according to a matrix score in the context of application in Scotland reflecting: storage capacity; cost; efficiency; technical maturity; Scottish infrastructure; CO2 emissions; public acceptability; environmental impact; and future potential advances. Figure 1 below shows the results, where the green bars are classified as energy storage technologies, and the pink as power quality technologies (i.e. providing short duration storage of seconds to minutes).

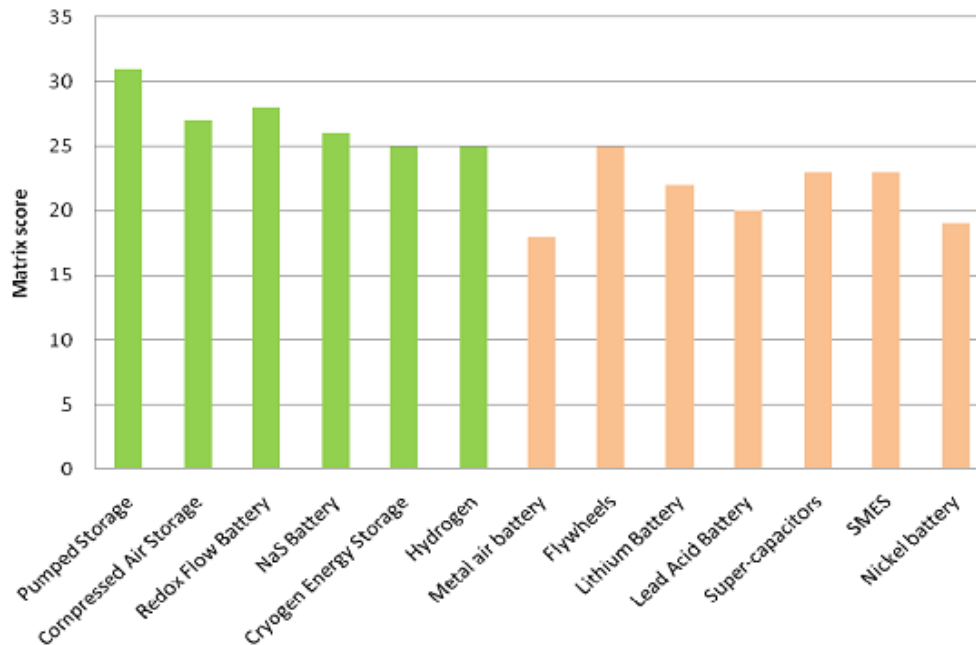


Figure 1: Ranking of energy storage options for Scotland¹²

¹² Energy Storage and Management Study; AEA 2010, for the Scottish Government.

2.2 Thermal Energy Storage – links with electricity

Denmark absorbs considerable surplus wind power in district heating systems simply by adding resistance heaters (or heat pumps) to existing systems. In 2010 this accounted for around 10% of heat supply. District heating systems already have considerable energy storage potential associated with the large volumes of water in use. This can be increased by adding hot water storage tanks to improve the flexibility of operation and capability to absorb surplus wind energy. Heat storage is easy to accommodate in this way, but the UK makes very limited use of district heating at present. There is scope for improved electric storage radiators to be deployed and linked to smart grid control systems. This is the approach being followed on Shetland where the lack of a cable to the mainland makes energy balancing for the electricity system difficult. It is also expected that heat pumps will be increasingly used for space heating, displacing gas, but adding to the loads on the electricity system. Recent research by the IEA is exploring the potential to apply demand side management to these heat pump loads, possible in highly insulated dwellings with large exposed thermal mass.

3. Discussion: Current and Future Energy Needs

3.1 Introduction

The Scottish Government seeks to achieve substantial decarbonisation of electricity generation by 2030, and of heat by 2050, with renewable energy and renewable electricity targets of 30% and 100% respectively by 2020. The evidence suggests that these targets can be met, although for electricity, much depends in the short to medium term on increased supply from onshore and offshore wind. In the longer term, Scotland aims to become a leader in the development and deployment of green energy on an international scale¹³. The potential for achieving these ambitions can be found in a range of technology sectors¹⁴.

3.2 Electricity consumption and generation

Gross electricity consumption (including transmission, distribution and generator's own use losses) in Scotland was of the order of 40 TWh in 2010. The total electricity generated in Scotland from all sources in 2010 was approximately 50 TWh per annum with roughly one third from nuclear, a quarter from coal, 10% from oil and gas, 10% from hydro, and 20% from wind (ie 10 TWh)¹⁵. The GB electricity system is currently dominated by conventional fossil fuel and nuclear plant. Exports of electricity from Scotland to England in 2010 at 10 TWh were about 20% of Scottish generation, and not that different from the amount of wind power generation in Scotland.

As noted above, renewable penetration is set to increase significantly, particularly in Scotland. Whilst present GB renewables penetration is still some way from requiring energy storage for operational

¹³ Ten Energy Pledges, [Scottish Government, 2009](#)

¹⁴ 2020 Routemap for Renewable Energy in Scotland, [Scottish Government, 2013](#)

¹⁵ Energy in Scotland: A Compendium of Scottish Energy Statistics and Information, Scottish Government, March 2012.

reasons, plans to increase onshore and, increasingly, offshore wind power mean it is important to consider available energy storage technologies.

It is widely accepted that energy storage has considerable potential in power systems with high renewables penetration. Experience in Europe provides some pointers to the challenges and how these might be addressed. For example, Denmark's remarkable achievement in integrating very high penetrations of wind¹⁶ is made possible through their connection to the Nordpool electricity trading system that includes Norway with its abundant hydropower generation resources¹⁷ and also pumped-hydro storage. Denmark is also connected through the European network¹⁸ to the German power system, and surplus wind power in Denmark is also sold to Germany. Without these network connections to other power systems it would be difficult for them to operate at such high wind penetration levels. In addition, Denmark has been retrofitting many of their district heating systems with electrical heating capabilities so as to be able to absorb surplus wind in this way and thus limit their Nordpool trading and retain more of the value of their wind within national boundaries. This is feasible technically due to the energy storage potential of such heating systems¹⁹.

3.3 Current Renewable Generation Profile

Scotland's renewable electricity generation has been growing steadily, mainly reflecting the growth of wind, as shown in Figure 2, with a total installed capacity late in 2013 of 6.5 GW²⁰. Solar photo voltaic (PV) capacity in Scotland has increased rapidly in the last years and now exceeds 100 MW. Hydro has long been a major renewable energy contributor; installed capacity is 1.5 GW, generating about 5 TWh per year. Scotland also has a major tidal stream potential in the Pentland Firth²¹ and funding is now in place for the first phase of the MeyGen project with a final potential of 398MW. When completed MeyGen could be the world's largest tidal energy array. In the longer term wave energy is also expected to be commercialised. None of these developments provide an immediate requirement for energy storage as all would be connected to the grid, which would be reinforced if required.

¹⁶ In 2013 wind production in Denmark corresponded to 33% of total electricity consumption, on a windy day more than half of the electricity used in Denmark is produced by wind power, and on a windy night the wind power share may exceed 120% of the Danish electricity load.

¹⁷ Note that the conventional hydro generation can also be operated to provide effective storage.

¹⁸ The European network is overseen by the European Network of Transmission System Operators for Electricity (ENTSO-E), an association of Europe's [transmission system operators](#) (TSOs) for electricity. It now contains 41 [TSOs](#) from 34 countries, which share an interconnected transmission grid in the EU.

¹⁹ Note that district heating systems *per se* only store very limited amounts of energy but can play a more significant role if additional storage is designed in or retrofitted.

²⁰ DECC Energy Trends data (ref)

²¹ Tidal turbines (much like wind turbines) extract energy from the flow, which in the case of the Pentland Firth can be up to 5 m/s.

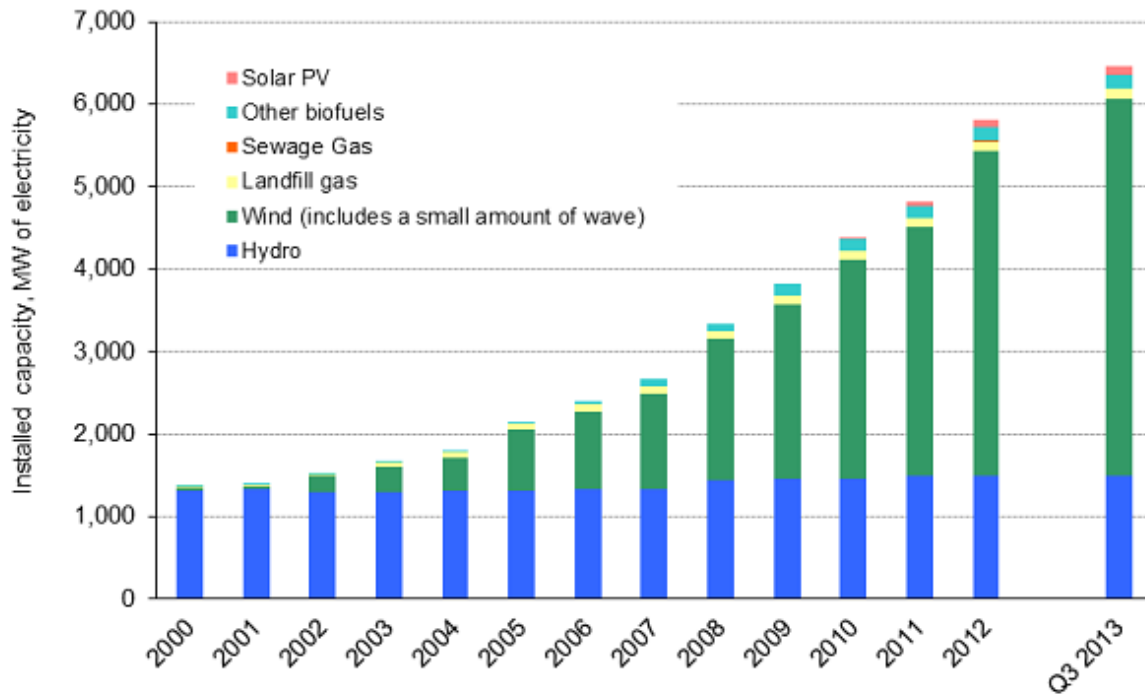


Figure 2: DECC Energy Trends data for Scotland up to the last quarter 2013.

It is expected that wind will continue to dominate the renewable electricity plant mix, although tidal stream energy is expected to start coming on line soon (see above). As wind is the major source of renewable supply for the short to medium term in Scotland, and presents a particular integration challenge because of its variability, most of the discussion on electricity storage below focuses on wind. However, significant solar photo voltaic penetration could present similar integration challenges.

3.4 Future Profile of Renewable Electricity in Scotland and GB

While Scotland currently operates within a GB-wide electricity market, the context for renewable energy policy is provided by the targets in the Climate Change (Scotland) Act 2009 for a 42% emissions reduction by 2020 and 80% by 2050, and by the Scottish Government's target to generate the equivalent of 100% of Scotland's electricity demand from renewable resources by 2020.

The best guide to the near future is the projects under construction and consented, and in the slightly longer term, those in planning. As of September 2013 Scotland had 4.6 GW of capacity either under construction or consented, mainly wind, with a further 9.4 GW in planning. This would take total renewable generation to 20.5 GW if all of this were constructed, which is roughly three times the present installed capacity.

Scotland has a renewable energy resource that is much larger than its projected energy needs. In the longer term we are therefore likely to see a significant increase in the export of renewable electricity, mostly to the load centres in England (mainly the Manchester area, the Midlands, and London and the

South-East), but later to the Continent through a series of High Voltage DC (HVDC) links like the one planned to Norway for 2020 (570 kilometres long and rated at 1.4 GW).

Two new HVDC ‘bootstraps’ are being constructed. These are offshore HVDC cables that will link to the north south AC transmission system to increase overall capacity. The £1bn offshore cable, known as the Western Link HVDC, should be operational by 2016 and will link Hunterston to Deeside. It will be rated at 2.4 GW and should increase the power transfer capacity between Scotland and England by approximately 2 GW. The Eastern Link HVDC (probably from Peterhead to Hawthorne Pit) is to be rated at 2 GW.

Since Scotland’s electricity system is part of the GB system it is also necessary to briefly review the renewables penetration expected for the GB system. Table 1 shows the projection of renewable energy, including electricity, required in the UK to meet the EU’s statutory 2020 target. This corresponds to approximately 29 GW of total installed renewable electricity generation capacity by 2020. Wind will clearly dominate and roughly two thirds of GB renewable electricity capacity will be in Scotland, putting a great burden of the interconnector (the onshore transmission link between Scotland and England). Even with recent reinforcement of the interconnector to 2.8 GW, this is not enough to accommodate plans for further wind capacity in Scotland. The two new bootstraps are therefore required to manage this flow.

	Central range for 2020 (TWh)
Onshore wind	24-32
Offshore wind	33-58
Biomass electricity	32-50
Marine	1
Biomass heat (non-domestic)	36-50
Air-source and Ground-source heat pumps (non-domestic)	16-22
Renewable transport	Up to 48TWh
Others (including hydro, geothermal, solar and domestic heat)	14
Estimated 15% target	234

Table 5: UK Renewable energy targets from DECC’s UK Renewable Energy Roadmap, July 2011

3.5 North-South power flows

Of course wind turbines do not operate at rated power all the time; typical capacity factors²² are in the range 0.25 to 0.35 onshore and higher offshore. During 2012 the installed wind capacity in Scotland was very roughly about 4 GW²³, which gives an average capacity factor of 29%²⁴.

It is clear that with the increase in renewable energy planned for Scotland by 2020 (around 20 GW, most of it wind) there will be times, when the wind is blowing hard across the country, that wind energy power will exceed the sum of the local load (3.4 GW as an average but much less than this during summer nights) and the total planned interconnector transfer capacity. In actuality during summer the wind is unlikely to blow in this way and this comparison is included simply to highlight the possibility.

An initial assessment of the issue of excess generation was undertaken by Sinclair Knight Merz for the Scottish Government.²⁵ Two scenarios were developed. The first to reflect the Scottish Government's aspiration to meet 100% of Scottish electricity demand from renewables by 2020; and the second where Scotland generates up to twice as much electricity as demand by 2020, with just over half of that generation coming from renewables. Detailed generation profiles were created for the two scenarios, and power flows across the Scotland to England boundaries were determined using half-hourly dispatch of plant based on merit order. The interconnector power flows were calculated for 2015, 2020 and 2030. Figure 3 shows the results for the first scenario, which relates to the Scottish Government's 2020 targets, in the form of duration curves.

²² Capacity factor is defined by actual generated output over an extended period of time/output if turbine was at rated power continuously during the same time period. Figures quoted are usually for annual average capacity factors.

²³ This is difficult to calculate accurately during periods of rapid installation where commissioning delays make the definition of capacity problematic, especially in relation to generation.

²⁴ Capacity factor (%) in this case = $(10/(4*8760/1000))*100$

²⁵ Scottish Generation Scenarios and Power Flows: An Analysis, Sinclair Knight Merz, 2011.

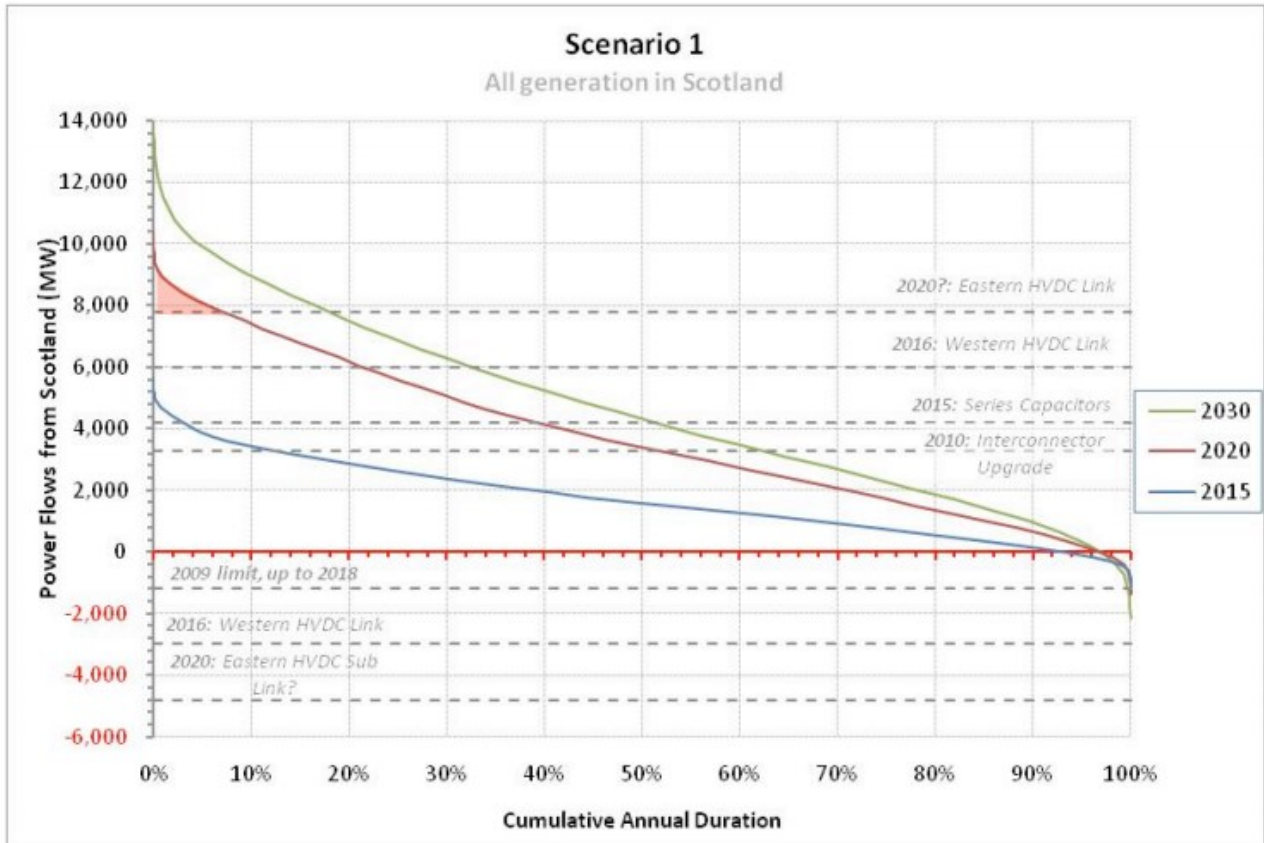


Figure 3: Duration curves for power flows from Scotland for 2015, 2020 and 2030 (taken from Scottish Generation Scenarios and Power Flows: An Analysis, Sinclair Knight Merz, 2011)

The 2020 curve shows that the power flow will exceed total network capacity for about 8% of the time (shaded red) even on the assumption that both Eastern and Western HVDC connections are in place. It should also be noted that it is assumed that all north south links can be operated at rated capacity whereas in reality power system stability can limit power flows on the AC sections to below thermal limits. HVDC connectors are not subject to such stability limits, indeed, suitably controlled, they can be used to improve the stability and thus power transfer of AC transmission. The differences between HVDC rated capacity and power transfer are so as to provide headroom to deal with transient demands. The cross border flows are strongly correlated with wind power production in Scotland as shown by Figure 4 below²⁶.

²⁶ HM Government report “Scotland analysis: Energy”, presented to Parliament by the Secretary of State for the Department of Energy and Climate Change, April 2014.

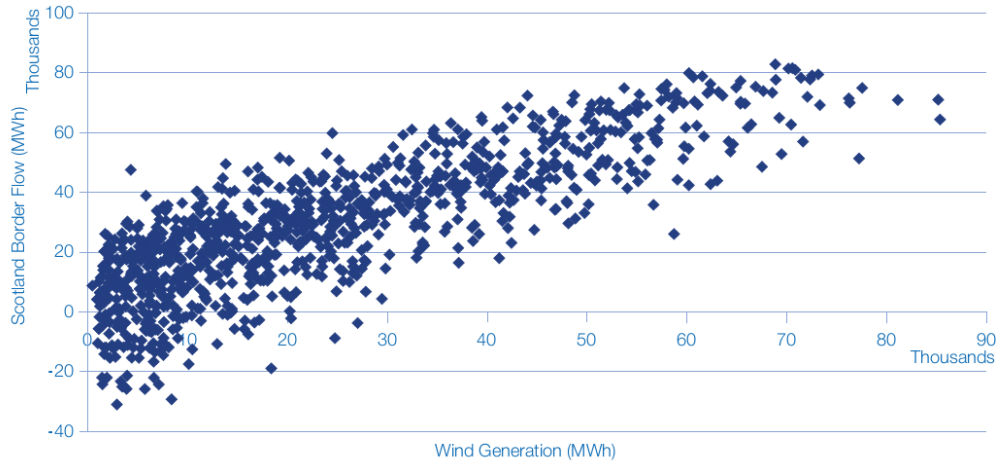


Figure 4: Cross border flows and Scottish wind power production

One way to deal with the variability of loading on the interconnector caused by wind power variation (in the main) is to **use storage to smooth the variations** and also to **ensure that maximum use is made of the interconnector's transfer capacity**. But this is not the only way in which storage can (and perhaps needs to be) used in a power system with high renewables penetration. To explain these roles the next section outlines briefly the generic wind integration challenge.

3.6 The Wind Integration Challenge

Wind is not the only renewable source that will be used in Scotland, but it will be the main source in the short to medium term, and is the most time variable and therefore the most challenging to integrate into the power system. This section discusses in outline the technical challenges of very high wind penetration. To do this a brief, non-technical overview of power system design and operation is provided.

The main operational challenge facing power system operators is to continuously match supply to demand²⁷. Very little energy is stored in the electricity system itself²⁸, and at most this inertial energy storage would last only some seconds supplying the system load. At this short time-scale, variations in total system load supplied by the power system are dealt with by governor²⁹ action on thermal (steam generating) plant. This short term regulation of the power system is often referred to as *frequency regulation*.

The power system electricity load profile depends in a fairly predictable manner on the time of year, the day of the week, and the time of day, reflecting the patterns of human behaviour. Power system

²⁷ See for example Leon Freris and David Infield; *Renewable Energy in Power Systems*, Wiley, 2009.

²⁸ This is associated with the spinning mass of generators (and also loads) that are synchronously connected to the power system (or near synchronously in the case of generation of loads connected via induction machines).

²⁹ Governors are regulators that adjust steam flow through adjustable valves in relation to the speed of the generator that reflects the power system frequency. Traditionally these were mechanical devices but they are now electronic.

operators (National Grid in the UK) have developed sophisticated methods for scheduling conventional plant to meet these expected changes in the system load (sometimes referred to as unit commitment) taking into account that large stations may take some hours to prepare for generation. Once a station is on line, economic dispatch³⁰ is used to determine what its power output should be at each point in time. Because load forecasts are imperfect, operators hold some flexible reserve (traditionally called spinning reserve), through part loading of some plant that can then rapidly adjust their output.

Power systems also have to cope with unexpected rapid change, such as following the sudden loss of a generating station or a transmission line due to some fault. The system operator will have primary and secondary reserves planned that can step in to cover such contingencies. These normally comprise part loaded thermal stations that can rapidly increase output when required, and also open cycle gas turbines that can be brought on line quickly. Pumped hydro systems can also contribute to loss of generation events, either by ceasing to pump, or by starting to generate.

Not all power generation has the flexibility that power system operators depend on in the manner outlined above. Renewable energy sources like wind and solar photo voltaic (PV) do not lend themselves to such stand-by operations. They are by their nature time variable, reflecting in the main, changes in the weather for wind and to a lesser extent solar, and time of day in the case of solar (and to a minor extent in the case of wind). In the UK, both vary notably with the time of year. Although variable, they are however fairly predictable, say 24 hours ahead.

Nuclear power also in practice lacks flexibility (due to the desire to maintain steady output levels whenever possible so as to limit thermal cycling and associated fatigue damage), but in a rather different way since it is not in general time varying. Like nuclear generation, renewables are capital intensive compared to conventional generation, but with low running costs, which is in the main due to low fuel costs in the case of nuclear, and no fuel costs for renewables. As a result, economics makes both of these into base load generation in the sense that it is preferable to run them whenever they are available.

One of the common complaints levelled against wind turbines is that the wind does not blow all the time, or to be more precise, the wind does not blow with the same strength at all times, but rather is constantly varying. Of course the statement is true but this does not mean that wind is incapable of making valuable contributions to electricity generation. Where they provide a minor proportion of total power supply, wind and other time-variable renewables can simply be viewed as reducing the net load, thus saving fuel use through conventional generation. This adds, to a limited extent, to the net load variation to be met by conventional plant³¹, but does not substantially increase the costs of this backup.

However as the proportion of energy supplied from renewable sources increases, the challenges of dealing with the variations, and matching supply to demand, increase, as do the costs. This is because

³⁰ Economic dispatch is the adjustment in time of a plant's output to reflect the short term demand on the power system and a calculation of the most economic manner of meeting this demand.

³¹ The total variation can be envisaged as the variation in wind power (or other time variable renewable) superimposed on top of the variation in the demand that would normally be met by conventional plant.

more conventional plant has to be operated below its rated output to provide the capability to respond to the fluctuations in the net demand and the penalty is reduced plant efficiency giving increased CO₂ emissions and higher conventional generation costs. It is here that storage can potentially play a role depending on costs.

3.7 The Role of Storage in Managing High Wind Penetration

Pumped-hydro is currently the preferred storage technology to help manage wind power variability. It can be used to absorb wind power that could not be exported to England due to transmission constraints and to release this energy at other times, potentially reducing imports to Scotland at times of peak local demand. Because of this and the expectation of increased wind capacity Scotland is in the process of increasing its pumped storage capacity³². The existing pumped hydro schemes in Scotland are Foyers (300 MW) and Cruachan (440 MW). This review also considers other, potentially more expensive storage technologies.

As well as causing operators difficulties in scheduling and dispatch of conventional generation due to increased time variability of the net load, a high penetration of wind and PV can also result in a lack of power system stability. Power system inertia is critical to the dynamics of power systems since it determines how much the power system frequency changes as a result of any temporal mismatch between generation and demand. Power system frequency must be maintained within tight limits to provide the power quality consumers require. Modern variable speed wind turbines use power electronics to supply the power system at a fixed frequency, but this has the role of removing the inertia of the wind turbine from the system. High penetrations of wind will also displace a substantial amount of conventional generation with its inertia, thus reducing the overall system inertia whilst at the same time increasing disturbances to the match between load demand and total generation that result from fast changes in wind power. The combined effect will be to reduce the stability margins, and if not dealt with could result in collapse of the system. Wind turbines can be controlled to emulate inertia but this is relatively unproven. One alternative is to add inertia through storage, ideally as real spinning mass, but also potentially as storage units controlled to emulate inertia. As well as frequency stability, there is also an issue of voltage stability in the event of faults on the system (usually some form of short circuit). Fast acting storage could be useful to deal with such events.

3.8 Current electrical storage activity in Scotland

Aside from the plans to extend pumped hydro storage, Scotland also plans to explore and demonstrate other energy storage technologies although most of these are at an early stage of development.

³² Consent for the 600 MW pumped hydro storage scheme at Coire Glas was granted in December 2013. It is awaiting a Final Investment Decision by SSE. SSE is also considering a scheme at Balmacaan that could deliver up to 600 MW. Consent was awarded to SSE for conversion of the conventional hydro system at Sloy to provide a 60 MW pumped hydro scheme. In February 2014, Scottish Power announced the start of a two-year feasibility study into plans to more than double the output of Cruachan to 1,040 MW.

The Orkney Energy Storage Park project is aimed principally at understanding what commercial markets are open to Energy Storage Providers (ESPs) for distribution networks. SSE Power Distribution intend to enter into a commercial contract with an Energy Storage Operator (ESO) that would install energy storage (most likely batteries) to help alleviate network constraints that are now limiting further wind capacity connection on the island.

SSE plans to install a 1 MW lead acid battery storage system on Shetland at Lerwick Power Station as part of wider development following the NINES project to identify the best mix of technologies for power generation, distribution and use on the island. This energy storage installation replaces an earlier plan using more advanced sodium-sulphur (Na/S) battery technology.

SSE have installed and successfully commissioned a 100kW (150kWh) demonstration flow battery system at its Nairn substation.

Scotland is presently testing hydrogen based electricity storage on three sites:

- Berwickshire Housing Association h-5 ecohome generates hydrogen through a 4.5kW electrolyser from surplus wind and solar electricity generated on site. This hydrogen is then reconverted to electricity through a 5kW fuel cell.
- The PURE Energy Centre generates hydrogen from on-site wind which is then used as either a transport fuel in a fuel cell/ battery hybrid vehicle or reconverted to electricity through a fuel cell.
- The Hydrogen Office is incorporating a store for 30kg of hydrogen under pressure. The hydrogen will be generated from surplus electricity from an on-site wind turbine and reconverted to electricity through a fuel cell.

4. Electrical Energy Storage Applications

The role that energy storage technologies fulfil varies according to their typical cycle times³³. Cycle times determine the use to which technologies are put. Ranges vary from seasonal times of weeks or months down to time scales as small as seconds to minutes. These use types are discussed below.

Short Term Cycle Uses (seconds to minutes)

Short term uses of energy storage are mostly associated with maintaining the stability of the power system, e.g emergency reserve to cover loss of plant or transmission lines. Such an application requires large power ratings, but only for seconds or minutes. Conventionally this is supplied by spinning reserve (i.e. part loaded plant), pumped storage, or open cycle gas turbines. Other storage technologies like flywheels could be an alternative. A key economic issue is that use of this supply is only occasional – at most a few times per year. Other uses include power system frequency regulation or voltage control and also providing angle stability (which relates to the electromechanical connection between the electrical

³³ The cycle time of a storage system is the typical time for a complete charge and discharge cycle.

generator and the grid that must be maintained if generation is not to be interrupted).

Intermediate Cycle Uses (hours to days)

Energy storage in electricity systems is most commonly aimed at intermediate time scales. These, most often larger scale systems, are usually for high energy use and thus on the scale of MWh of storage. There are a few key applications.

Load shifting, load leveling or peak shaving are all part of a subset of load management activities that can be delivered by storage. This use focuses on moving or shifting pieces of the load often to reduce the peak load. Commonly, peak shaving involves storing surplus energy from renewables and discharging the storage during a time of high demand. Load leveling, on the other hand, which may also reduce the peak, usually involves charging the storage from the grid during times of low demand and then discharging during a peak. The following graph in Figure 4 shows an example of load leveling³⁴.

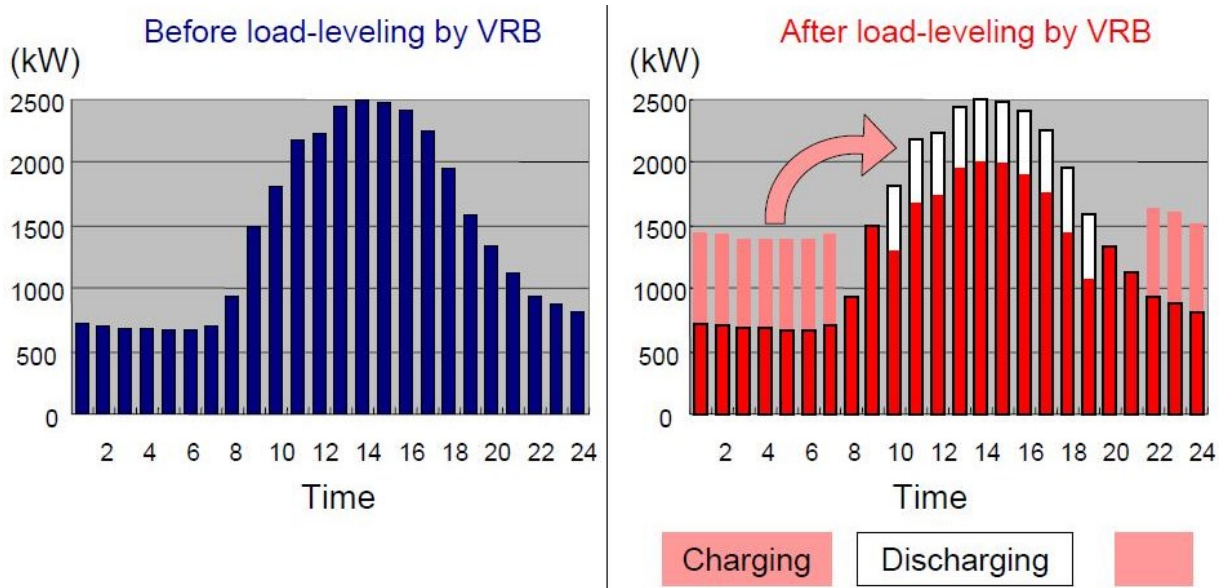


Figure 5: Load Leveling/Peak Shaving Sample (Source: Climate Tech Wiki³⁵)

The other key usage for storage of intermediate cycle length is the ability to store energy generated from renewable sources, usually when more electricity is generated than can be absorbed by the power

³⁴ Both of the graphs pictured would be the load as seen by the grid/utility. The left graph is a sample load graph. On the right side, the impact of a large scale storage system (a Vanadium Redox Battery) is presented. The light pink portion is when the battery is being charged. The white tops of the load curve shows when the battery is discharging. If we discount the pink portion of the right graph, the result would be similar to peak shaving as the stored energy would need to have come from some other source.

³⁵ www.climatetechwiki.org

system at a given time. The energy generated through renewable sources is much less responsive to supply and demand, and thus flexible conventional generation is required, or perhaps energy storage, to ensure a secure supply.

Table 6 from the Purdue University report³⁶ tries to capture these electrical storage uses, their benefits, and the timeframes within which they operate.

	Required Response Time	Reference Duty Cycle	Energy Discharge Cycle Duty	ES System Unit Power (MW _{AC})	ES System AC Voltage (kV)	Full Power Discharge Duration	Basis for Economic Benefits
3 hour Load Shift	10 minutes	Scheduled 3 hour discharge	60 days/year 1 event/day	1 to 200	4.2 to 115	3 hours	market rates
10 hour Load Shift	10 minutes	Scheduled 10 hour discharge	250 days/year 1 event/day	1 to 200	4.2 to 115	10 hours	market rates
Renewables time shift	1 minute	Optimized by technology	Per reference wind profile	2 to 200	4.2 to 34.5	5 to 12 hours (except CAES; varies)	Various*
Renewables forecast hedging	20 milliseconds	Optimized by technology	Per reference wind profile	2 to 200	4.2 to 34.5	5 to 12 hours (except CAES; varies)	Various*
Fluctuation suppression	20 milliseconds	Continuous cycling	90 cycles/hour	2 to 50	4.2 to 34.5	10 seconds	Various*
Short duration power quality	20 milliseconds	Hot standby	100 events/year 5 events/day 1 event/hour	1 to 50	4.2 to 34.5	5 seconds	cost of alternative solutions
Long duration power quality	20 milliseconds	Hot standby for infrequent events	1 event/year	1 to 50	4.2 to 34.5	4 hours	cost of alternative solutions
Frequency excursion suppression	20 milliseconds	Hot standby	10 events/year 1 event/day	10 to 500	4.2 to 750	15 minute	cost of alternative solutions
Grid frequency support	20 milliseconds		24 events/year 1 event/day	2 to 200	4.2 to 34.5	10 to 30 minutes	Various*
Angular stability	20 milliseconds	Hot standby	10 events/year 1 event/day 20 Cycles/event	10 to 500	4.2 to 750	1 second	cost of alternative solutions
Voltage stability	20 milliseconds	Hot standby	10 events/year 1 event/day	10 to 500	4.2 to 750	1 second	cost of alternative solutions
Transmission curtailment	1 minute	Optimized by technology	Per reference wind profile	2 to 200	4.2 to 34.5	5 to 12 hours (except CAES; varies)	Various*

*indicates various bases for economic benefits of these applications include capitalized costs and benefits of alternative systems, market rates, tax credits, and green price premiums.

Table 6: Energy Storage Uses and Statistics

Long Term Cycle Uses (weeks to months)

This form of energy storage applies less to electrical energy and more to thermal energy although pumped storage can be used in theory to cover such periods of time.

With thermal storage, heat or cold can be stored for use to compensate for long term cycles in energy supply of need, for example associated with the seasons. At its longest this would be called inter-seasonal storage.

³⁶ R. Carnegie, D. Gotham, D. Nderitu and P. Prekel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report form State Utility Forecasting Group, University of Purdue (June, 2013)

5. The Economics of Energy Storage

Large-scale energy storage is expensive, and, as described above, pumped hydro storage is generally seen as the only cost effective way to store electricity at this time. Other technologies are under development, and some like batteries are well developed but require further cost reductions.

Few studies have been completed that attempt an overview of storage economics considering all the possible sources of value generation including arbitrage (which is the term used to describe the financial opportunities associated with load levelling as a result of the differences in generation costs between peak and low load periods), network services (such as frequency response and voltage control), and deferred investments in plant and the transmission and distribution system. One such study by Imperial College³⁷ focused on the UK concluded that 'Bulk and distributed storage are found to provide most value when placed in Scotland and Southern regions'. The value of storage was not surprisingly found to be highly dependent of the penetration of RE into the power system. Figure 6 is taken from this report and represents the value of 10GW of distributed energy storage.

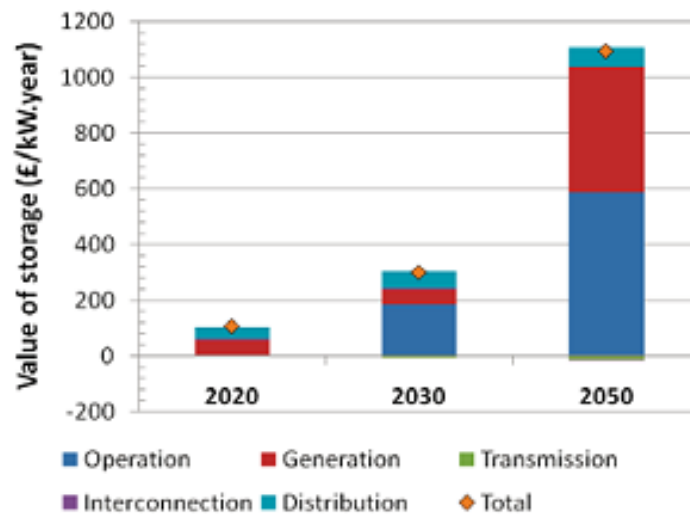


Figure 6: Value of storage for 2020, 2030 and 2050

The main changes between the different years shown in the figure are the assumed levels of renewable energy operating in the power system. Alternative approaches, such as flexible generation, flexible demand through demand side management or greater network interconnection will reduce the value of storage. Imperial College's modelling assumed the UK to be self-secure (i.e. that UK generation capacity is sufficient to meet peak demand and with sufficient reserve margin held within the UK to cover uncertainties, or equivalently that no contribution to system security from interconnectors from outside the UK is allowed). If this assumption were relaxed then the value of the energy storage would be

³⁷ Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future; Report for the Carbon Trust by the Energy Futures Laboratory, Imperial College, June 2012.

reduced, perhaps significantly. Since the future system requirements are driven by carbon reduction targets, the wide scale use of flexible Carbon Capture and Storage (CCS) fitted generation would reduce the need for storage dramatically since this plant would be adjusted in time to compensate for variations in RE generation. To a great extent therefore, CCS and storage are either or options, although storage might still be attractive for peak shifting provided it was cheap enough, i.e. cheaper than CCS fitted generation as a source of capacity. An important conclusion of the study is that ‘bulk storage should predominantly be located in Scotland to integrate wind and reduce transmission costs, while distributed storage is best placed in England and Wales to reduce peak loads and support distribution network management³⁸.

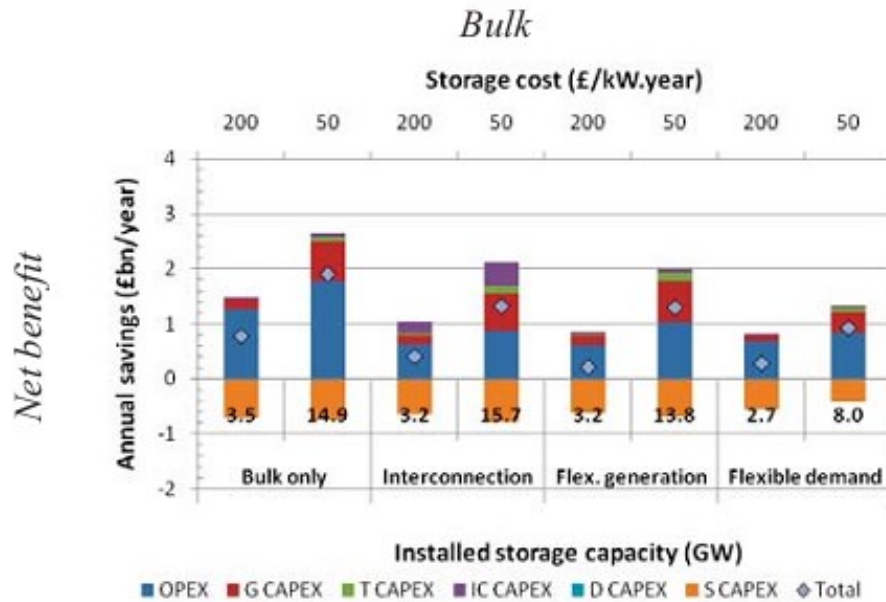


Figure 7: Impact of competing technologies³⁹

Figure 7 shows how competing technologies affect the net value of energy storage investments. Not surprisingly interconnection, flexible generation and flexible demand (demand side management) all significantly reduce the value of storage. These values apply to the UK power system as a whole. A study focusing on the value to Scotland of storage in Scotland could be undertaken along similar lines; this would require assumptions such as no dependence on the rest of the UK for security of supply. In practice this is unlikely to occur since the costs of electricity both in Scotland and also in the rest of the UK would be higher as a result.

Given that Figure 6 shows most of the benefit of energy storage occurring in the long term (its value in 2050 being at least ten times that in 2020), it is natural to consider when such investments should be made. Analysis, such as AEA’s, suggest that in the nearer term, interconnection is more cost effective:

³⁸ This relates primarily to management of congestion in distribution systems in the face of distributed generation or increased loads, for example for electric vehicle battery charging.

³⁹ G denotes generation; T transmission, IC interconnection, D distribution, and S storage.

based on scenarios for 2020 and 2030⁴⁰ they conclude that interconnection, above that planned and using HVDC technology, would be cheaper than new pumped hydro storage. It should also be noted that the energy losses would be considerably lower. Moreover, unlike pumped storage (or CAES) there are no geographical or geological siting constraints that would limit the available capacity. This same report includes an extensive presentation of demand side management (DSM) but no analysis of its potential contribution. Figure 7 from the Imperial College (2012) study however makes it clear, as would be anticipated, that use of DSM detracts from the value of energy storage. In effect DSM makes use of intrinsic energy storage associated with certain loads (like hot water, or space heating). Future loads such as expected to come from electric vehicle (EV) charging, also have a great deal of flexibility.

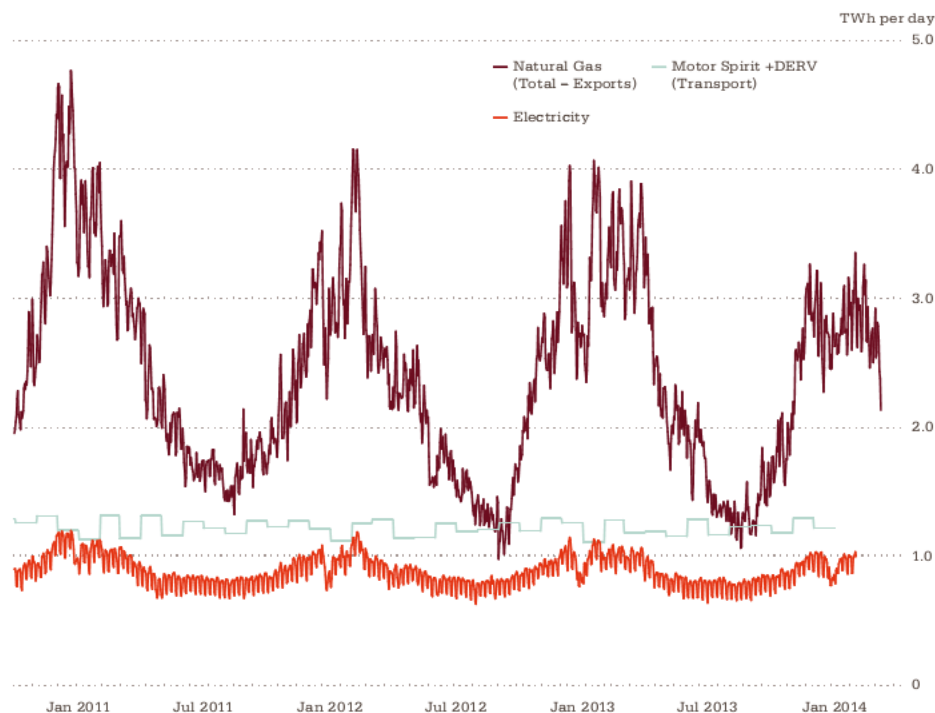


Figure 8: Annual variation in energy consumption

If an increasing proportion of space heating is to be provided by electricity from RE sources as required to reduce dependence on gas, then the enormous seasonal variation in consumption shown in Figure 8 above, has to be dealt with. This really does emphasize the importance of reducing the demand for space heating both in domestic and commercial buildings. To attempt to meet these heat demands with electricity, even using heat pumps with good COPs, would require simply massive investments in generation, transmission and distribution. Fortunately there is much that can be done to improve the thermal performance of buildings, but this is a long term task and needs to be addressed seriously in a manner so far not undertaken in Scotland (or the rest of the UK). Super-insulated homes with heat pumps would also offer opportunities for DSM and internal temperatures would be quite stable and

⁴⁰ But note that neither of these scenarios is exactly consistent with the present Scottish Government plans.

allow a degree of flexibility in the timing of heat input.

Also apparent from Figure 8 is the substantial (non-electric) energy used for transport. If any significant proportion of this was replaced by electricity through the charging of EVs then care would need to be taken not to overload the electricity system. Studies have shown that demand side management would be essential, since without this most EV users would tend to recharge their EVs on return from work, exactly at the time of peak electricity demand in the UK. However, because EVs are typically only in use for about 5% of the time, there remains plenty of time for charging and thus charging can be rescheduled to minimise impact on the electricity system without inconveniencing vehicle users. It has also been suggested that EV batteries could be discharged at times of peak electricity demand; such operation is often referred to as Vehicle to Grid (or V2G). Used in this way the batteries are being used as electricity storage for the power system. Care is however required as vehicle batteries are expensive and V2G use means additional charge/discharge cycles that will shorten the battery life, and so such use may not end up being cost effective.

It would seem that decarbonisation of energy supply must go hand in hand with DSM. This will reduce the value of dedicated energy storage systems. Much more detailed studies would need to be undertaken to assess if and when further bulk energy storage systems would be justified in Scotland.

6. Conclusions

In the long term (2050), it is clear that energy storage technologies have considerable potential as a key component of an efficient, stable and secure low carbon energy system. With very high levels of renewable energy (including for heat and transport), energy storage may well have considerable value, although this will depend critically on other developments, in particular Carbon Capture and Storage (CCS) and demand side management.

For Scotland, as an exporter of renewable electricity to England, further reinforcement of the north south transmission capacity is a cheaper and more effective option than large-scale electrical storage, at least in the short-medium term.

The evidence examined in this study demonstrates that pumped hydro is widely accepted as the cheapest form of energy storage. Scotland has further potential and at least one company is seeking to develop additional capacity, notwithstanding the inevitable environmental impact. In the longer term, sea pumped hydro could be attractive and could complement offshore wind. This is an option that merits more detailed investigation and research.

Despite decades of research and development hydrogen technology remains very expensive and still has very low round trip efficiencies, making it relatively unattractive as electricity storage. Some communities find hydrogen systems attractive when a range of energy services can be met directly from hydrogen including heating, cooking and transport, and such approaches are being demonstrated in Scotland. Such demonstrations require considerable external funding at present and in some cases

cheaper alternatives can be identified, such as for the NINES project on Shetland where a mix of thermal and battery storage for the island, coupled to demand side management is being used. There is however interest from researchers in generating hydrogen from surplus electricity and adding this to the gas distribution system at an acceptably low percentage mix, thereby storing some hydrogen in the gas transmission and distribution system, and avoiding the inefficient reconversion to electricity. These developments should be monitored closely.

Battery storage systems are being installed despite their high present costs, and demonstration systems should be carefully assessed. Commercial improvements in battery technology should be monitored.

Developing and improving energy storage technology is an expensive business and the rewards highly uncertain. It would be better for Scotland to focus R&D efforts on system analysis, rather than technology development, but to track international and commercial developments.

Since energy storage can potentially add value to electricity systems in a number of ways (arbitrage, peak-opping, reserve, frequency control, transmission and distribution investment deferral) it is important that market operation (such as non-cost reflecting tariffs) does not give unfair advantage to other approaches, in particular the investment in new generation plant. Market developments need to be assessed carefully in this context.

Terminology/Glossary of Terms

- Power – Electricity being consumed or generated at a specific instance in time. Units in Watts
- Energy – Amount of power consumed over time. Mathematically it is the area under the power curve or can be the product of power and time. Units in Watt-Hours
- Cycles – The combination of a charging and discharging operation of the energy storage.
- Round Trip Efficiency – Total energy actually charged/discharged during a cycle. Some percentage less than 100. There are separate efficiencies for charge and discharge operations, but it could be combined into a single round-trip value.
- Anode – Substance where the currents flows to in battery storage
- Cathode – Substance where the current flows from in battery storage
- Oxidation – Reaction where a chemical loses its electrons
- Reduction – Reaction where a chemical gains electrons
- Depth of Discharge – The percentage of the battery's energy that has been discharged during the previous cycle
- Superconducting – Phenomenon where the internal resistance of an object has gone to zero Ohms. Currently requires objects to be cooled to very low temperatures in order to achieve

List of useful websites

1. Websites Used for Illustrative Purposes

- <http://www.creighton.edu/green/energytutorials/formsofenergy/storingenergy/>
- <http://www.electrochemsolutions.com/battery/resources.aspx>
- <http://www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento/almacenamiento.html>
- <http://www.tantaline.com/Flow-Batteries-568.aspx>
- <http://gigaom.com/2011/07/12/how-ultracapacitors-work-and-why-they-fall-short/>
- <http://www.intechopen.com/books/dynamic-modelling/dynamic-modelling-and-control-design-of-advanced-energy-storage-for-power-system-applications>
- <http://www.green-planet-solar-energy.com/hydrogen-fuel-cells.html>
- <http://www.climatetechwiki.org/sites/ climatetechwiki.org/files/images/extra/load%20leveling%20with%20VRB.JPG>
- <http://www.greenspec.co.uk/building-design/biomass/>

2. Websites Used for Additional Information

- <http://energystorage.org/>
- <http://www.mpoweruk.com/chemistries.htm>
- <http://www.scotland.gov.uk/Resource/Img/328702/0096203.gif>
- http://batteryuniversity.com/learn/article/secondary_batteries
- <http://www.climatetechwiki.org/sites/ climatetechwiki.org/files/images/extra/load%20leveling%20with%20VRB.JPG>
- <http://www.mpoweruk.com/life.htm>
- http://www.chpa.co.uk/what-are-energy-maps_245.html
- http://en.wikipedia.org/wiki/District_heating#Heat_distribution
- <http://www.euroheat.org/>

Other material reviewed

AEA Technology, "Energy Storage and Management Report," October 2010

Abbas A. Akhil, Georgianne Huff, et. al., "DOE/EPRI 2013 Electricity Handbook in Collaboration with NRECA," July 2013

Oghenetejiri Anuta, Andrew Crossland, et. al., "Regulatory and Financial Hurdles for the Installation of Energy Storage in UK Distribution Networks," CIRED Workshop, May 2012

Charles J. Barnhart, Michael Dale, et. al., "The energetic implications of curtailing versus storing solar- and wind-generated electricity," Energy & Environmental Science, 2013

Marc Beaudin, Hamidreza Zareipour, Anthony Schellenberglobe, William Rosehart, "Energy storage

for mitigating the variability of renewable electricity sources: An updated review,” *Energy for Sustainable Development* 14, 2010, pages 302 – 314

Rajni Burra, “Grid Performance – GE Brilliant Turbines,” EWEA 2014

Rachel Carnegie, Douglas Gotham, et. al., “Utility Scale Energy Storage Systems: Benefits, Applications, and Technologies,” June 2013

Community Energy Scotland, “Scottish Government Energy Storage Workshop,” March 2013

Community Energy Scotland, “CARES Infrastructure and Innovation Fund Update,” March 2013

K.C. Divya, Jacob Ostergaard, “Battery energy storage technology for power systems – An overview,” *Electric Power Systems Research* 70, 2009, pages 511 – 520

Energy Research Partnership, “The future role for energy storage in the UK Main Report,” June 2011

Gerda Gahleitner, “Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications,” *International Journal on Hydrogen Energy* 38, 2013, Pages 2039 – 2061

R. Gazey, S.K. Salman, D.D. Aklil-D’Halluin, “A field application experience of integrating hydrogen technology with wind power in a remote island location,” *Journal of Power Sources* 157 (2006), pages 841 – 847

Ariful Haque and Mir Ashikur Rahman, “Study of a Solar PV-powered Mini-grid Pumped Hydroelectric Storage & Its Comparison with Battery Storage,” 2012 7th International Conference on Electrical and Computer Engineering, December 2012

Institution of Mechanical Engineers, “Electric Storage,” May 2012

International Energy Agency, “Technology Roadmap: Energy Storage,” 2014

International Energy Agency, “Energy Storage Technology Roadmap: Technical Annex A and B,” March 2014

International Energy Agency, “IEA Energy Storage Technology Roadmap Launch,” March 2014

Irena (International Renewable Energy Agency), “Thermal Energy Storage: Technology Brief,” January 2013

The Jimmy Reid Foundation, “The Future of the Energy Storage Industry in Scotland,” January 2014

KEMA, “Market Evaluation for Energy Storage in the United States,” 2012

Vladimir Koritarov, “Grid-Scale Energy Storage,” PSERC Webinar, September 2013

Peter Lang, Steward Reid, et. al., “State of Charge of GB,” Energy Storage Operators’ Forum,

November 2013

Eric Lounsbury, "The future of energy storage in the UK – Power in unity: a whole system approach," October 2013

Faber Maunsell (AECOM), "The Potential and Costs of District Heating Networks," A report to the Department of Energy and Climate Change," April 2009

Marcelo Gustavo Molina, "Dynamic Modelling and Control Design of Advanced Energy Storage for Power System Applications," Dynamic Modelling, January 2010, page 290

Susan M. Schoenung and William V. Hassenzuhl, "Long- vs. Short-Term Energy Storage Technologies Analysis," August 2003

The Scottish Government, "2020 Routemap for Renewable Energy in Scotland – Update," December 2013

The Scottish Government, "Energy in Scotland 2014: A Compendium of Scottish Energy Statistics and Information"

The Scottish Government, "Energy Statistics for Scotland," December 2013

Professor Peter Taylor, "Delivering flexibility in a low carbon energy system: What role for energy storage in the UK?," Seminar on "Resetting the energy markets," March 2014

V. Viswanathan, M. Kintner-Meyer, et. al., "National Assessment of Energy Storage for Grid Balancing and Arbitrage: Phase II: Volume 2: Cost and Performance Characterization," September 2013

Pengfei Wang, Daniel H Liang, et. al., "Integrating Electrical Energy Storage Into Coordinated Voltage Control Schemes for Distribution Networks," IEEE Transactions on Smart Grid, Vol. 5, No. 2, March 2014

APPENDIX – Review of Electricity Storage Technologies Available

The following sections cover those types of energy storage considered to be viable, and include short descriptions of how the technology works, unit sizes available and associated costs. The different types of storage technology are categorized as: mechanical; electrical; and chemical storage.

1 Electrical Energy Storage

1.1 Mechanical Storage

Mechanical energy storage is storage in either the form of kinetic or potential energy. Three kinds are presented here: pumped hydro, compressed air, and flywheels. Pumped hydro and compressed air store water or air at a higher potential energy to be later released and generate electric energy. Flywheels store kinetic energy to later be utilized for electricity generation.

Pumped Hydro

Pumped hydroelectricity storage is the dominant large scale electricity storage technology around the world due to its relatively low cost. It is a type of mechanical energy storage where water flow is used to generate or release the stored energy into the system. Generally, pumped hydro is the most mature technology of the various energy storage types available and has the lowest costs per unit of stored electricity. A large amount is already installed. Current global pumped hydro capacity is around 127 GW⁴¹.

The general operational flow of pumped hydro is the following. Electricity is used to pump water to a reservoir at a higher altitude. When there is a demand for the energy, the water is passed to a lower reservoir through a system of turbine generators thus converting the mechanical energy of the water to electrical energy to be fed into the grid. Figure A1 below⁴² shows the two modes of operation for pumped hydro.

⁴¹ September 2013 presentation by Vladimir Koritarov of Argonne National Laboratory [ref 1].

⁴² www.creighton.edu

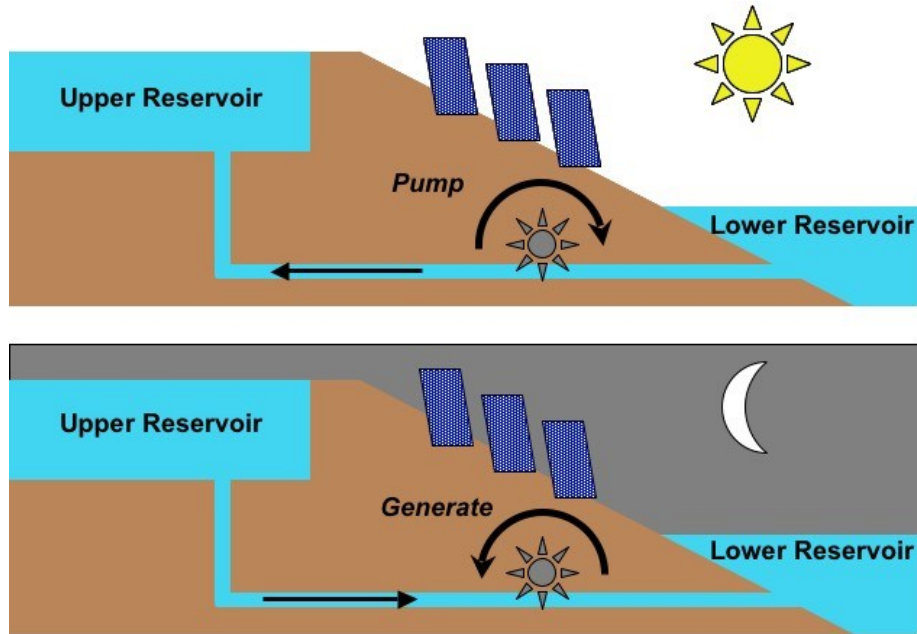


Figure A1: Pumped Hydro Flow

Due to its size and the length of time over which pumped hydro storage can be used, it is seen predominately as long term storage. It has discharge windows ranging up to around 10 hours. Therefore, it can be used to substantially reduce peak loads on the power system. To do so, the system will usually pump water to the upper reservoir during low demand (and thus low cost) intervals and then release the water during high demand (and high cost) intervals in order to reduce the peak load to be met from conventional plant. In doing this it can considerably improve the load factor of other plant operating within the power system.

Partly due to the maturity of the technology, there is a large number of operational projects and associated documentation regarding the capabilities of this technology. A pumped hydro storage plant has energy storage ratings in the GWh range and power ratings from hundreds of MW to around 1 – 2 GW. On average, the efficiency of pumped hydro storage is around 75% although there are projects with efficiencies in the 80% range. In addition, pumped hydro storage has a lifetime that is much longer than most other types of energy storage. The civil works have an almost indefinite lifetime if properly maintained, while the turbines and generators will last many decades.

Environmentally, pumped hydro storage has both benefits and drawbacks. The benefit is clearly the ability to limit use of fossil fuel generation by reducing the need to use peaking units that generally rely on fossil fuels for generation. Problems include siting – finding a site for both of the reservoirs may be difficult – and construction, which can have long-term effects on the surrounding environment.

Projects are usually able to recoup their costs, mainly as a result of long equipment lifetimes of well over 10,000 cycles. This far exceeds that of other storage technologies currently. Costs are presented in Table

A1 below which was compiled in a Purdue University report using data from EPRI⁴³.

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (Cycles)	Total cost (\$/kW)	Cost (\$/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Small Pumped Hydro	Mature	1,680-5,300	280-530	6-10	80-82	>13,000	2,500-4,300	420-430
Large Pumped Hydro	Mature	5,400-14,000	900-1,400	6-10	80-82	>13,000	1,500-2,700	250-270

Table A1: Pumped Hydro Storage Costs

An important factor to consider in these costs is that construction costs vary greatly depending on location. Site-specific costs may vary significantly from the values presented above.

At present there are two pumped hydro facilities in Scotland, shown in Table A2.

Station	Capacity (MW)	Head (m)	Response Time	Energy Stored (GWh)
Cruachan	400	396	2 mins from stationary 30 sec if spinning	8.8
Foyers	300	197	2 mins from stationary	6.3

Table A2: Scotland's Pumped Hydro Storage

Scottish & Southern Energy have plans at various stages of development for a further three installations with a total capacity of around 1.3 GW: a 300-600 MW pumped storage station at Balmacaan; a 600 MW installation at Coire Glas; and a smaller 60MW conversion of the Sloy hydro system. SSE also plans an extension of Cruachan from its present 400 MW up to potentially 1,040 MW.

The above information focused on more conventional pumped hydro storage, but there are other applications. One alternative to conventional pumped hydro is seawater pumped hydro in which the lower water reservoir is the sea. This allows greater flexibility in siting although capital costs are estimated to be higher due to the need for the pump to be corrosion resistant. Additional costs may be associated with creating a suitable upper storage reservoir. To date only one such system has been installed, a 30 MW unit in Japan. Scotland's extensive coastline should provide opportunities for this technology but there has been no detailed evaluation so far of the potential. Clearly, the higher the sea cliffs, the more cost effective the installation. And being coastal, such storage could provide a useful complement to marine renewable power generation.

A further variation is underground pumped hydro where caverns or abandoned mines are used for the lower reservoir, and a lake (or even the sea) used for the upper reservoir. No systems have been built or have had detailed cost estimates presented, and therefore must be regarded as speculative at this point in time.

⁴³ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report from State Utility Forecasting Group, University of Purdue, June 2013

Compressed Air Energy Storage (CAES)

Compressed air storage is a relatively mature energy storage technology, but there are few demonstration projects highlighting its capabilities. CAES relies on storing energy during low cost/low demand times and then using it at a later time. Energy is stored as compressed air, which is mixed with hydrogen or natural gas and then passed through a combustion turbine to generate electricity – see Figure A2⁴⁴.

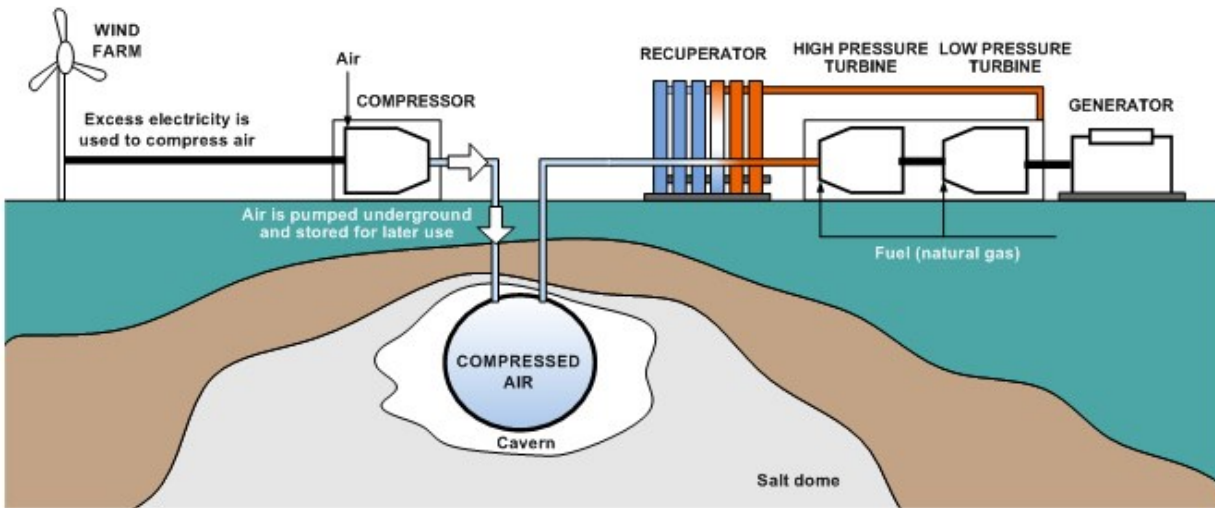


Figure A2: Compressed Air Energy Storage

CAES sizes vary depending on usage needs. Larger systems are usually designed to generate energy for a minimum of 5 hours, with power ratings of 300 to 400 MW that can run for around 10 to 30 hours. Smaller systems typically have power ratings of 10 to 20 MW and a time range less than 5 hours. In terms of efficiency, CAES systems vary greatly, but most fall in the range of 73 – 89%.

The air compression vessel is usually stored below ground. For larger facilities, the vessel may be: salt caverns, hard rock caverns, porous rock formations, abandoned mines, pipes, and underwater bladders. Vessel construction has a very large effect on the efficiency of the system. Two current facilities using salt caverns/domes for the vessel have not had issues associated with leaking which would contribute to a loss in efficiency.

Advantages and disadvantages are very similar to those of a pumped hydro storage system: the main advantages are reduction of peak loads and thus hopefully of use of fossil fuel peaking power plants, and the ability to integrate CAES technology in wind generation systems. But building or siting CAES facilities is quite difficult. The high pressure required for the storage and the gases present in the storage system present major risks. These include damage to the vessel and risk of explosion.

In terms of costs, CAES is very similar to pumped hydro storage. The facilities have a large up-front cost, but their long life and low operation and maintenance costs slightly balance it out. As Table A3 shows,

⁴⁴ www.sc.ehu.es/sbweb/energias-renovables/temas/almacenamiento/almacenamiento.html

costs are heavily dependent on the cavern used for the facility.

Geology	Capital Costs
Salt Cavern (Solution Mined)	\$1/kWh
Salt Cavern (Dry Mined)	\$10/kWh
Hard Rock (Excavated & Existing Mines)	\$30/kWh
Porous Rock / Aquifer	\$0.10/kWh
Abandoned Limestone or Coalmines	\$10/kWh

Table A3: Compressed Air Energy Storage Geology Costs⁴⁵

Table A4 shows some possible costs in terms of sizing.

	Size	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Lifetime (Cycles)	Total cost (\$/kW)	Cost (\$/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
CT-CAES ²⁸ (underground)	Small	Demonstration	1,400-3,600	180	8	>13,000	960	120
	Large	Demonstration	1,400-3,600	180	20	>13,000	1,150	160
CAES (underground)	Small	Commercial	1,080	135	8	>13,000	1,000	125
	Large	Commercial	2,700	135	20	>10,000	1,250	60
Time shift, capacity credit, and transmission and distribution support								
CAES (aboveground)	Small	Demonstration	250	50	5	>10,000	1,950-2,150	390-430

Table A4: Compressed Air Energy Storage Costs⁴⁶

Although this technology is rather mature, due to the difficulty associated with siting, there are few active demonstration projects. Tellingly, numerous projects have started construction, but never reached operation. Two projects have been cancelled in the United States because the sites were deemed unable to handle the CAES facility. Smaller CAES facilities (typically above ground) do not have these problems.

The two that are constructed are:

- Huntorf, Germany – Began operations in 1978, uses a salt dome for the pressure vessel, has a capacity of 290 MW and can be charged in 12 hours and discharged within 4 hours at maximum capacity;
- McIntosh, Alabama (USA) – Began operations in 1991, also uses a salt dome, capacity is 110 MW and can have a maximum output time of 26 hours.

To date no suitable sites for underground CAES have been identified in Scotland⁴⁷. Surveys in Scotland

⁴⁵ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report from State Utility Forecasting Group, University of Purdue, June 2013

Operation and Maintenance costs are explored further in the Purdue report.

⁴⁷ Though survey work has identified sites in England, Wales and Northern Ireland – see <http://www.scotland.gov.uk/Resource/Img/328702/0096203.gif>

have confirmed there are no viable salt cavern formations in Scotland⁴⁸. There may be suitable abandoned coal caverns, but further studies would need to be done to determine the viability of constructing CAES systems in Scotland.

Flywheels

Flywheels store electric energy as kinetic energy by rotating a mass within the system. The charging operation is performed by having electric energy drive a motor that will spin the mass. Discharging has the spinning mass drive a motor-generator to produce electricity. A sample image of the system is provided in Figure A3.⁴⁹

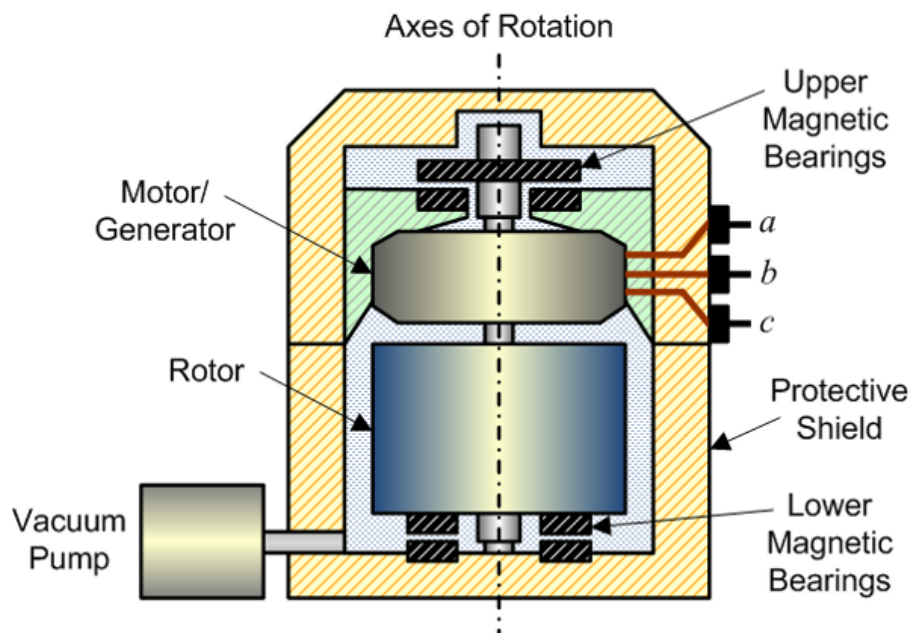


Figure A3: Flywheel Construction Diagram

In general, flywheels provide short term storage. This is due to the fact that the kinetic energy of the mass has a much larger self-discharge or loss as the result of friction. Additional elements like the vacuum pump shown above aim to reduce the friction in the system to increase efficiency. Proper construction and materials can achieve efficiency in the range of 70-80%.

Flywheels' short term storage means they are principally used for maintaining power quality or reliability (frequency regulation).

The advantages and disadvantages for flywheel technology are almost the opposite of those for pumped hydro storage. Flywheels are easy to site as they are modular and represent a relatively simple

⁴⁸ AEA Group – Energy Storage and Management Study, October 2010

⁴⁹ “Dynamic Modelling and Control Design of Advanced Energy Storage for Power System Applications” by Marcelo Gustavo Molina, January 2010

construction project.

Williams Advanced Engineering have acquired a manufacturer (previously Eurenco) of advanced composite flywheel motor/generators. These flywheels are packaged with a power electronics grid interface to provide a complete stand-alone storage system. It is planned to demonstrate these on the Scottish islands of Eigg and Fair Isle where they would support the present renewable based electricity systems and where short term energy storage should significantly improve system operation.

Key disadvantages are that a structural deficiency in the system could result in the rotor becoming dislodged, representing a hazard, and the noise from the system. Careful planning is needed to deal with these problems.

Costs are relatively high - see Table A5⁵⁰.

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (Cycles)	Total cost (\$/kW)	Cost (\$/kWh)
Grid Support and Power Quality								
Flywheel	Demonstration	5	20	0.25	85-87	>100,000	1,950-2,200	7,800-8,800

Table A5: Flywheel Cost Data

1.2 Electrochemical Storage

Electrochemical storage stores electrical energy within a chemical medium. Principal technologies are batteries and fuel cells. Batteries can be divided into many groups and vary greatly depending on their chemistry, chiefly lead-acid, lithium ion, and sodium sulphur. The following sections cover the key technologies.

Electrical/Battery Storage

The chemical reaction occurring in batteries is the transfer of electrons between the chemicals in the cells. Batteries are a very common form of energy storage, but have some limitations that prevent widespread adoption.

In the reaction for electrical battery storage, the charge and discharge vary based on the flow of electrons between the anode and cathode of the battery. Figure A4⁵¹ shows this process.

⁵⁰ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report from State Utility Forecasting Group, University of Purdue, June 2013

⁵¹ <http://www.electrochemsolutions.com/battery/resources.aspx>

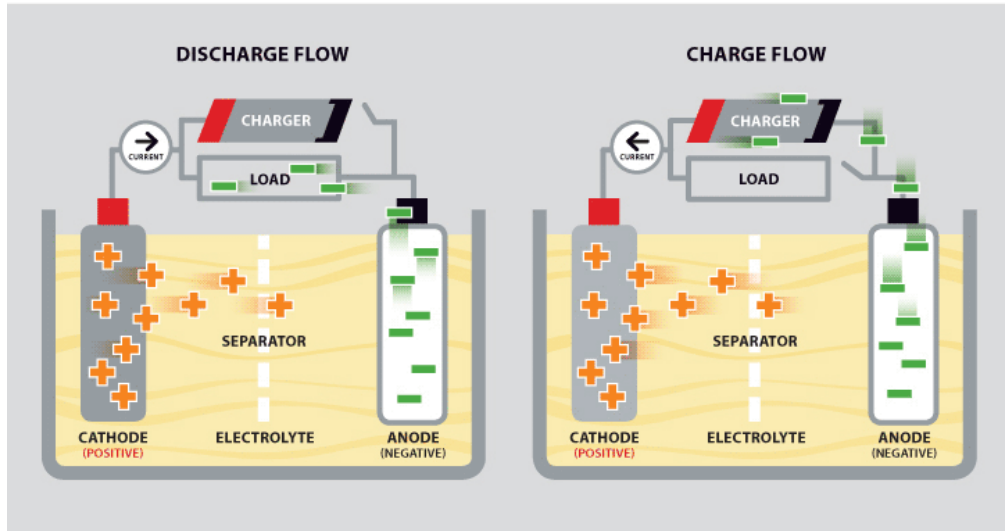


Figure A4: Battery Storage Operation

Batteries have a wide range of applications, mainly due to their ability to quickly switch modes of operation between charging and discharging. Applications include frequency regulation, peak shaving/load leveling, and renewable output smoothing.

Battery size and power output have a very wide range. Figure A5⁵² compares sizes for different chemistries.

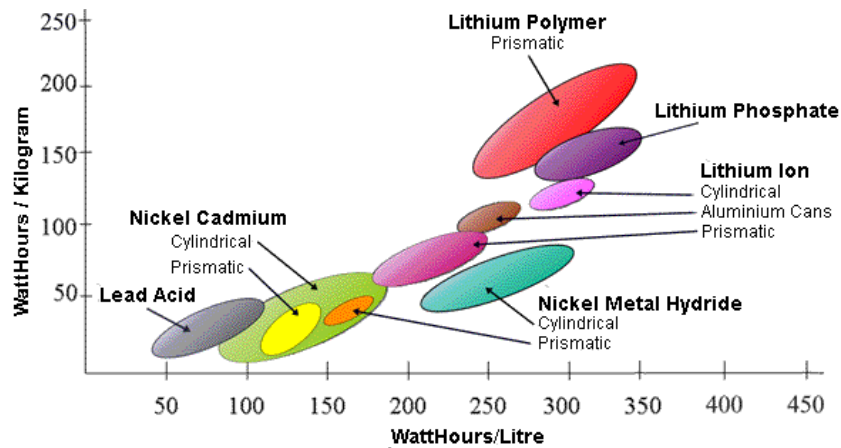


Figure A5: Battery Sizing Comparisons

Although battery technology has been around for quite a long time, it has numerous technical limitations. Due to the nature of the reaction occurring, battery technologies have a much shorter lifetime than storage such as pumped hydro. Lifetimes vary greatly between the chemistries and are improving as production methods continue to improve. Table A6⁵³ presents characteristics of common

⁵² <http://www.mpoweruk.com/chemistries.htm>

⁵³ http://batteryuniversity.com/learn/article/secondary_batteries

battery chemistries⁵⁴.

Specifications	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific energy density (Wh/kg)	30–50	45–80	60–120	150–190	100–135	90–120
Internal resistance ¹ (mΩ)	<100 12V pack	100–200 6V pack	200–300 6V pack	150–300 7.2V	25–75 ² per cell	25–50 ² per cell
Cycle life ⁴ (80% discharge)	200–300	1000 ³	300–500 ³	500–1,000	500–1,000	1,000–2,000
Fast-charge time	8–16h	1h typical	2–4h	2–4h	1h or less	1h or less
Overcharge tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge		
Self-discharge/month (room temp)	5%	20% ⁵	30% ⁵	<10% ⁶		
Cell voltage (nominal)	2V	1.2V ⁷	1.2V ⁷	3.6V ⁸	3.8V ⁸	3.3V
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20		3.60
Discharge cutoff voltage (V/cell, 1C)	1.75	1.00		2.50 – 3.00		2.80
Peak load current Best result	5C ⁹ 0.2C	20C 1C	5C 0.5C	>3C <1C	>30C <10C	>30C <10C
Charge temperature	–20 to 50°C	0 to 45°C		0 to 45°C ¹⁰		
Discharge temperature	–20 to 50°C	–20 to 65°C		–20 to 60°C		
Maintenance requirement	3–6 months ¹¹ (topping chg.)	30–60 days (discharge)	60–90 days (discharge)	Not required		
Safety requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory ¹²		
In use since	Late 1800s	1950	1990	1991	1996	1999

Table A6: Battery Chemistry Comparisons

⁵⁴ The information in Table A6 is a little out of date and there may have been improvements in these numbers, but this shows the general picture for batteries.

Cycle numbers are heavily dependent upon the manner in which the source is used. For example, by having a lower depth of discharge per cycle, it is possible to further extend the useful lifetime of the battery – see illustrative pattern in Figure A6⁵⁵.

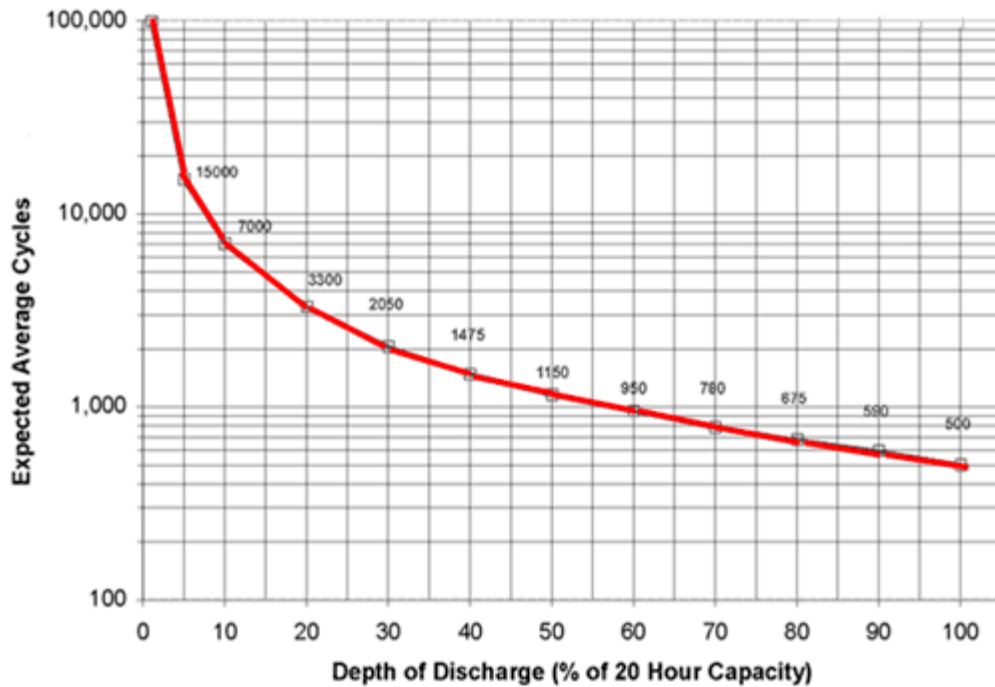


Figure A6: Battery Cycle Depth of Discharge Comparison

Batteries' environmental impact is a complicated proposition. In general, production and recycling require high fossil fuel and material inputs. On the other hand, batteries generally require less space and heavy engineering than pumped hydro, making them relatively easy to deploy. Battery storage can be used to affect peak demand – though its effect would likely be smaller than those of pumped hydro storage or CAES. Batteries can also be used in other ways to benefit power system stability.

Battery costs vary alongside capabilities. Even across similar chemistries, there can be a wide spread of costs depending on the production methods used. More environmentally friendly production methods increase production costs. Tables A7 – A9 present cost data for three prevalent technologies⁵⁶.

⁵⁵ <http://www.mpoweruk.com/life.htm>

⁵⁶ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report form State Utility Forecasting Group, University of Purdue, June 2013

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (cycles)	Lifetime (Cycles)	Total cost (\$/kW)	Cost (\$/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Advanced Lead Acid	Commercial	200	50	4	85-90	(2200)	1700-1900	425-475
	Commercial	250	20-50	5	85-90	(4500)	4600-4900	920-980
	Demonstration	400	100	4	85-90	(4500)	2700	675
Grid Support and Power Quality								
Advanced Lead Acid	Demonstration	0.25-50	1-100	0.25-1	75-90	(>100,000)	950-1590	2770-3800
Time shift, capacity credit, and transmission and distribution support								
Advanced Lead Acid	Demonstration	3.2-48	1-12	3.2-4	75-90	(4500)	2000-4600	625-1150

Table A7: Lead Acid Battery Costs

Battery usage can greatly affect lifetime and costs. In particular, the grid support demonstration has a cycle lifetime approximately 100 times that of the typical lead acid battery.

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (cycles)	Total cost (\$/kW)	Cost (\$/kWh)
Power quality, capacity credit, and intermittent renewables integration								
Lithium Ion	Demonstration	0.25-25	1-100	0.25-1	87-92	>100,000	1085-1550	4340-6200
Time shift, capacity credit, and transmission and distribution support								
Lithium Ion	Demonstration	4-24	1-10	2-4	90-94	4,500	1800-4100	900-1700

Table A8: Lithium Ion Battery Costs

Once again, use can have a large effect on the various costs and lifetime of the equipment. Note that, because lithium ion technology is less mature than lead acid, varying production methods mean the range of costs is larger .

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (cycles)	Total cost (\$/kW)	Cost (\$/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Sodium Sulfur	Commercial	300	50	6	75	4,500	3100-3300	520-550
Time shift, capacity credit, and transmission and distribution support								
Sodium Sulfur	Commercial	7.2	1	7.2	75	4,500	3200-4000	445-555

Table A9: Sodium Sulfur Battery Costs

A short report entitled, "State of Charge of GB"⁵⁷ shows numerous batteries of varying chemistries either being installed or already in service in Britain – see Figure A6.

⁵⁷ Energy Storage Operators' Forum Report, "State of Charge of GB," November 2013

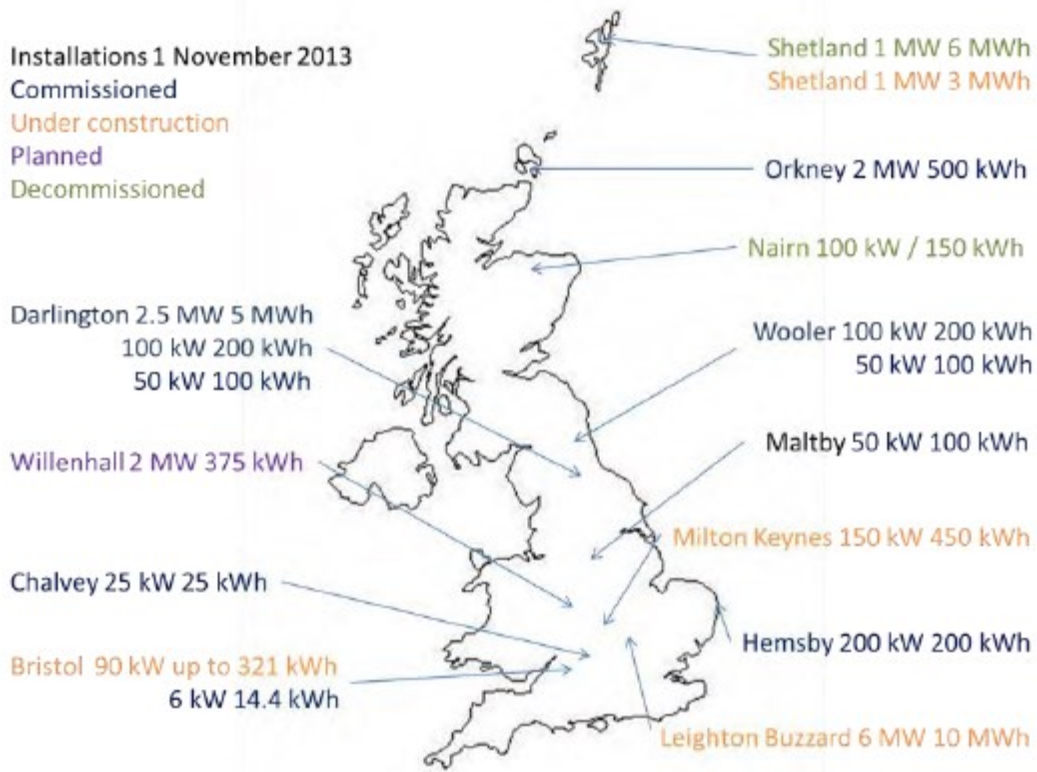


Figure A6: Battery Installations in Great Britain

Such battery storage systems are not presently economically attractive - these installations have been funded by the Low Carbon Networks Fund (LCNF) and Innovative Funding Incentive (IFI) established by Ofgem. Whether these installations will become economic in the future depends on many factors, discussed in the conclusions to this report.

In Scotland, battery storage systems are most likely to be installed near substations (either the 11kV primary sub-stations or at the smaller distribution substations) since they can then help alleviate loads on the distribution system and thus provide enhanced value. Practical issues include availability of space, as these substations are mostly located near or in residential areas where space is limited, and fire risk. If such storage units do become cost effective in the future, these issues can certainly be overcome, and the trial systems allow the DNOs to become familiar with installation and operational issues.

Flow Batteries

Flow batteries are a very specific subset of batteries. The fluid in the cells is stored and pumped during charge and discharge times for the chemical reaction to occur. Flow batteries are used mostly for long term discharge periods (greater than 5 hours) because the battery may be made larger simply by

increasing the volume of the tanks storing the fluid. A sample system is shown in Figure A7⁵⁸.

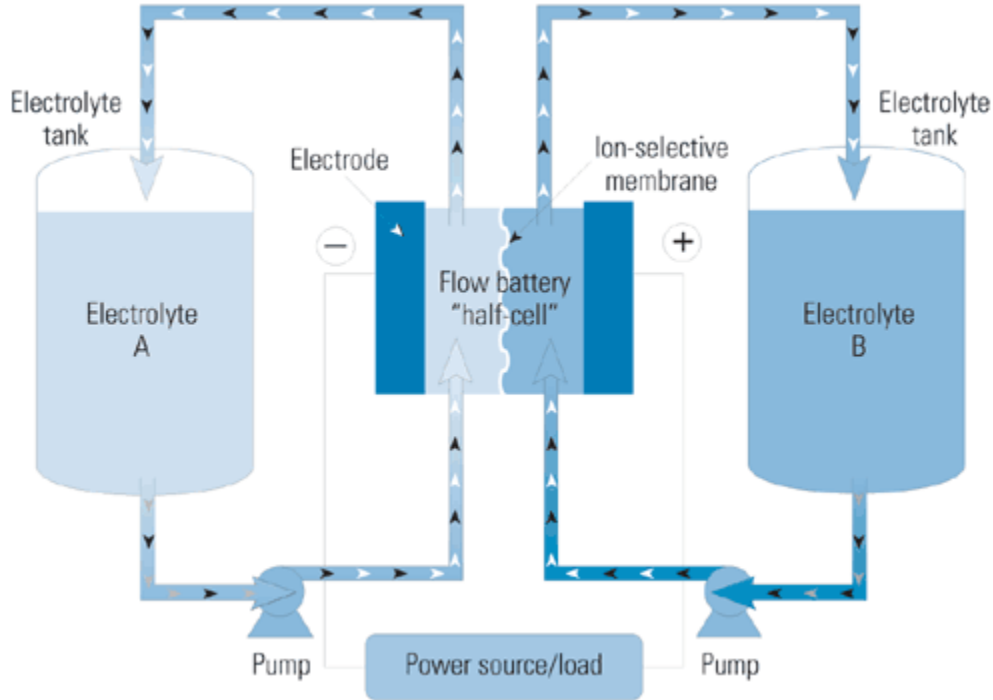


Figure A7: Flow Battery Operations

Although these batteries can be scaled larger relatively easily to increase the amount of energy in the system, there are some distinct disadvantages similar to pumped hydro rather than batteries. The increased system complexity requires higher amounts of construction and equipment. This causes more possible points of failure and thus increased maintenance costs in comparison to conventional batteries. In addition, the usage of the pump system results in more points for a reduction in the efficiency of the system.

Similar to conventional batteries, there are multiple chemistries for flow batteries. These two chemistries are hybrid flow and redox flow batteries. In general, flow batteries commonly fall into the second category of redox batteries. Within this subset of flow batteries, there are two chemistries to discuss: Vanadium redox and Zinc Bromine. VRB is the most common type and thus will be the focus of the following discussion.

Vanadium redox batteries (VRB) have been in development and are able for purchase and have been used in numerous scenarios. Of particular interest, VRB have been used for renewable integration (both solar and wind), load leveling, and power quality/reliability stabilization. The storage capacity of VRB is heavily dependent on the volume of the electrolyte within the battery. An example from the Purdue report cites a 10 MWh battery requiring between 12,000 and 17,000 square feet which is double the space requirement for a similarly sized conventional battery.

⁵⁸ <http://www.tantoline.com/Flow-Batteries-568.aspx>

VRB generally have a large cycle life north of 10,000 cycles. This is approximated at 1,000 cycles per year from around 10 to 15 years. The equipment within the system may need more maintenance as discussed with the pumps and other equipment, but generally this life is quite long and not a problem. VRB efficiency however is generally lower at 60 to 70% in comparison to conventional batteries. This is the result of the additional equipment. Some uses for VRB is shown below in Table A10⁵⁹.

Application	Size	Duration	Plant Capacity	Response Time	Duty Cycle	Roundtrip Efficiency	Plant Footprint	Environmental Impact
DR/Peak Shaving	0.5–25 MW	4–8 hours	1 MWh–100 MWh	1–10 min	20–50 events/yr	Low (<70%)	0.002 MW/m ²	Low noise; aesthetics depends upon location; medium emissions
Spinning Reserve	1–1000 MW	2 hr	2–2000 MWh	10 min	5–60 events/yr	Low (<70%)	0.002 MW/m ²	Low noise; medium emissions
Windfarm Stabilization & Dispatch	100 kW–100 MW	4–8 hours	0.5–800 MWh	1 sec (stability)	Continuous for stability (when operating); 10–50 events/yr for dispatch	Medium (70–90%)	Not a constraint – windplant space available	Low emissions; medium aesthetics

Table A10: Vanadium Redox Battery Uses

VRB are the more common flow battery, particularly due to simplicity and advantages of its construction. This is due to the chemicals being able to mix without contaminating each other. This would result in self-discharge of the VRB, but this is a smaller problem than other flow batteries. In addition, the chemicals used in the VRB is not poisonous or corrosive vapors. The membrane in the battery is toxic, but in general VRB are much easier for permits and siting as there are not emissions or fuel handling requirements associated with it.

As a brief display of the costs, Table A11 shows some of the costs and sizing for some of the demonstration projects out there.

⁵⁹ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report form State Utility Forecasting Group, University of Purdue, June 2013

	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	Efficiency (%)	Lifetime (cycles)	Total cost (\$/kW)	Cost (\$/kWh)
Grid support (ancillary services) and integration of intermittent renewables								
Vanadium Redox	Demonstration	250	50	5	65-75	>10,000	3100-3700	620-740
Time shift, capacity credit, and transmission and distribution support								
Vanadium Redox	Demonstration	4-40	1-10	4	65-70	>10,000	3000-3310	750-830

Table A11: Vanadium Redox Battery Costs

Hydrogen (Electrolysers, Storage and potential reconversion to electricity using Fuel Cells)

Hydrogen Fuel Cells are a constant discussion of item when discussing energy storage. Similar to electrochemical batteries, there is a large push within the engineering and manufacturing communities. This has a lot to do with the fact that it is widely seen as a clean and effective method of storing energy. The basic layout/operation of the hydrogen fuel cell works as follows. Water is pumped into the system and is converted by electrolysis into its constituent elements: hydrogen and oxygen. The hydrogen is eventually recombined with oxygen in a fuel cell (although this stage can be replaced by combustion in a suitably modified engine) and there is a resulting energy release. This process is depicted in Figure A7⁶⁰. Round trip (electricity to electricity) efficiency is poor, mainly due to limitations on fuel cell efficiency.

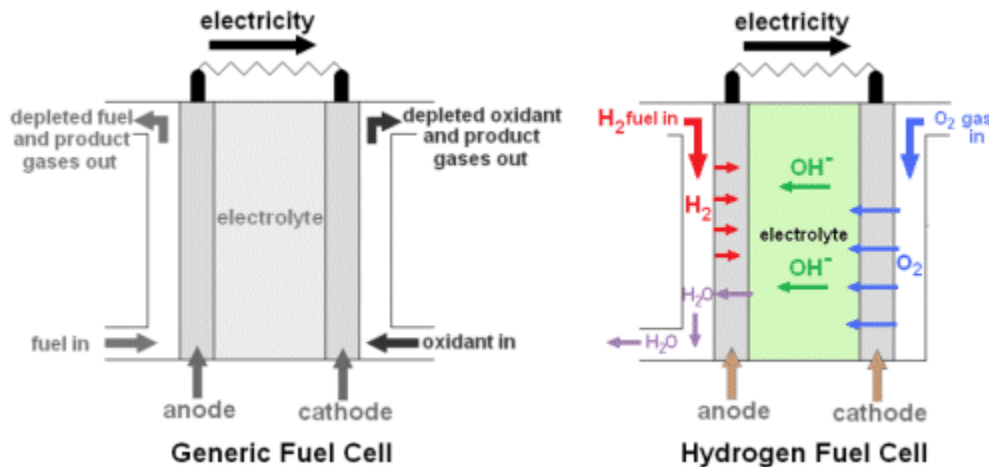


Figure A7: Fuel Cell Operation

Part of the interest in fuel cells (specifically hydrogen) is the idea that the main input and output of the system is water. The cell/storage size can accommodate numerous uses like those of electrochemical batteries and pumped hydro storage. The fact that the system is versatile and seen as less environmentally impactful as other storage types makes it seem to be more appealing.

A huge problem with this currently however, is that there is little to no hard data about these systems. What is known beyond these advantages are some major disadvantages. As part of an Energy Storage review performed by the University of Calgary dated in 2010, much detail went into discussing the much

⁶⁰ <http://www.green-planet-solar-energy.com/hydrogen-fuel-cells.html>

higher costs currently associated with fuel cell technology. Costs estimates were between \$500 and \$10,000 per kW. There are some expectations for this to drop to \$15 to \$145 per kW by 2020, but this is still a large unknown. These costs are much larger than those of other energy storage technologies which could solve the same problems at lower cost.

The interesting part to note about both electrochemical batteries and fuel cells is the interrelationship they have. Both are seen as not only storage for the grid, but also as an alternative to the combustion engines for automobiles. Much work has gone into (and is currently going into) making them a more viable option in terms of costs. Depending on how electric car and hydrogen car usage and networks evolve/develop could rapidly change both the costs and viability of these storage options.

Another difficult point in discussing fuel cell technology is the results and true capabilities of the system. Numerous reports on demonstration systems for fuel cell technology are still collecting data on the system performance and thus the results are currently not presented. Therefore, technical data capturing the efficiencies, power ratings, and other costs are not able to be presented in this report.

In summary, hydrogen technology remains very expensive and very low round trip efficiencies make it unattractive as electricity storage. Some communities, such as on the Island of Unst, find hydrogen systems attractive when a range energy services can be met directly from hydrogen including heating, cooking and transport. Hydrogen from electrolysis is soon to be used to power a fleet of fuel cell powered electric buses in Aberdeen, with in principal the electricity coming from a nearby offshore wind farm. To date though such communities have been protected from the very high capital costs of such systems, and there are also challenging operational issues, particularly with regard to health and safety. There is however an increasing interest in generating hydrogen from surplus electricity and adding this to the gas distribution system at an acceptably low percentage mix, thereby storing some hydrogen in the gas transmission and distribution system, and avoiding the inefficient reconversion to electricity.

1.3 Electrical/Magnetic Storage

This type of storage is a lot less prevalent and has many less options to go over. In general, electrical storage stores the energy which some kind of magnetic/electric field to use the energy at a later time. Therefore, in addition to the capacitor itself, there will be a short explanation of some of the expanded systems that are possible with the capacitors installed.

Super/Ultra Capacitors

Capacitors as a general electrical device, store electrical energy within an electric field. This usually has electrical conducting materials separated by a non-conducting material. In conventional capacitors, the storage capacity of the capacitors is determined by the surface area of the conducting plates.

Conventional capacitors however, lack the energy storage capability truly required for power system energy storage. Therefore, a newer form of storage that is an electrochemical capacitor (also known as super/ultra-capacitors) is examined.

The construction of a super/ultra-capacitor is similar to that of a battery. There is an electrolyte fluid in

the capacitor that assists in the storage of the energy. The main difference however is that the capacitor stores energy statically instead of the chemical manner done in conventional batteries. A basic layout of the capacitor design is shown in the following: Figure A8⁶¹.

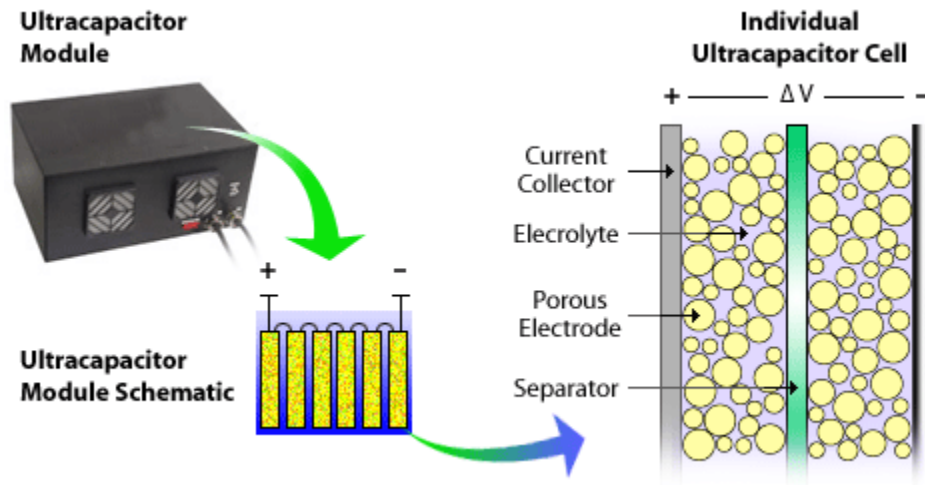


Figure A8: Super/Ultra-Capacitor Design

A large benefit of the ultra-capacitor is its cycle life. In general, it is many times larger than that of conventional batteries. There are however many disadvantages to them that are similar to batteries. First, if any of the individual ultra-capacitor cells begin to fail, it could result in the rapid degradation of the others in the module. Another major issue is in the siting and recycling of the equipment. The siting is not too dissimilar from conventional batteries and there needs to be concern given to the possibility of explosion. The new issue however is the current lack of any programs in terms of recycling the ultra-capacitors.

In terms of usage, even though the ultra-capacitor has a higher energy density than that of traditional capacitors, the uses are limited to the shorter term. Things such as power system stability type operations would be the more common usages. The costs and usages are shown in Table A12⁶².

⁶¹ <http://gigaom.com/2011/07/12/how-ultracapacitors-work-and-why-they-fall-short/>

⁶² R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report from State Utility Forecasting Group, University of Purdue, June 2013

	Angular Stability	Voltage Support	Short Duration Power Quality
Capacity (MWh)	0.003	0.003	0.006
Initial costs (\$/kW)^a			
PCS	153	153	153
BOP	100	100	100
Storage	162	162	203
O&M cost (\$/kW-year)^b			
Fixed	11.9	11.9	13.1
Variable	6.7	6.7	6.8
NPV Disposal cost (\$/kW)	0.2	0.2	1.5
Total Capital Cost (M\$)	4.1	4.1	4.6

NOTES: *indicates application estimates are in 2004\$

a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.

b. Fixed O&M costs include projected annual labor, parts, tax, and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

Table A12: Super/Ultra-Capacitor Costs

Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) is less likely to fit the needs of Scotland with the integration of renewables, but it is none the less an interesting storage technology to present if needs change.

SMES stores energy in a magnetic field generated within a superconducting coil. This coil can then be discharged to release the stored energy. In order to maintain the energy stored in the coil, there is refrigerant system to maintain an environment suitable for superconducting. The basic system layout is shown in Figure A9⁶³.

⁶³ <http://www.intechopen.com/books/dynamic-modelling/dynamic-modelling-and-control-design-of-advanced-energy-storage-for-power-system-applications>

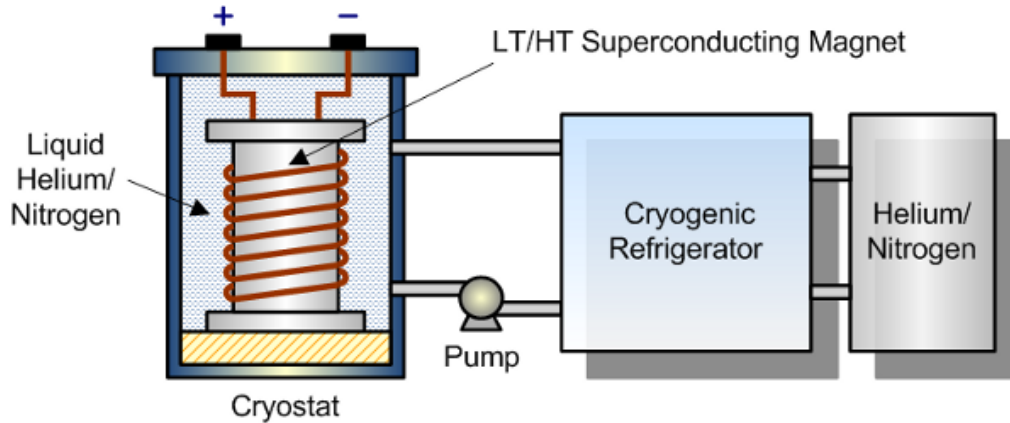


Figure A9: Superconducting Magnetic Energy Storage Layout

The SMES is typically used for shorter duration discharges which is very similar to ultra-capacitor storage. In general, SMES is highly efficient and does not have some of the negatives of most other storage. Its efficiency is upwards of 95%, which is due to superconductive nature of the materials. In addition, it is possible to begin discharge very quickly and the equipment lifetime is independent of cycles which is quite different from typical storage equipment.

Even with these benefits, the system has major drawbacks. The need for the refrigeration system is quite expensive. In addition, the refrigeration system requires its own energy source to run as well. These costs are captured in Table A13⁶⁴.

⁶⁴ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report form State Utility Forecasting Group, University of Purdue, June 2013

	Angular Stability	Voltage Support	Short Duration Power Quality
Capacity (MWh)	0.003	0.003	0.006
Initial costs (\$/kW)^a			
PCS	120	120	150
BOP	50	50	50
Storage	207	207	309
O&M cost (\$/kW-year)^b			
Fixed	14.5	14.5	22.2
Variable	8.7	8.7	12.4
NPV Disposal cost (\$/kW)	0	0	0
Total Capital Cost (M\$)	3.8	3.8	5.1

NOTES: *indicates application estimates are in 2004\$
a. Initial costs include acquisition, space, and installation costs. PCS means power conversion system and BOP means balance of plant. Total initial cost can be calculated by multiplying the sum of CT, BOP, and Storage initial costs by the reference power.
b. Fixed O&M costs include projected annual labor, parts, tax, and insurance costs. Variable O&M costs include fuel and other variable consumables and assume a duty cycle appropriate for each application.

Table A13: Superconducting Magnetic Energy Storage costs

These costs are from 2003, but that appears to mostly due to the adoption of the storage. As stated, the general use is limited to things such as system stability. Three of the units currently in operation are in Table A14⁶⁵.

Start of Operation	Host	Location	Application
June 2000	Wisconsin Public Service	Northern Wisconsin	Transmission Loop Voltage Stability - 6 Units, installed at distributed locations
July 2000	Alliant Energy	Reedsburg, Wisconsin	Transmission Voltage Stability
May 2002	Entergy	North Texas	Voltage Stability - 2 Units

Table A14: SMES Operational Systems

⁶⁵ R. Carnegie, D. Gotham, D. Nderitu and P. Preckel; Utility Scale Electricity Storage Systems – Benefits, Applications and Technologies. Internal report form State Utility Forecasting Group, University of Purdue, June 2013

Hybrid Systems – Battery with Capacitors

Rather than focusing much on the actual costs of these systems, this section will give some references of hybrid systems and how they are used. In general, these systems can be used to meet to needs and have high power ratings as well as high energy ratings. This can be accomplished by having the capacitor portion cover the short burst associated with high power, while the other portion (commonly batteries) can go for longer time periods and thus be the high energy portion. The following literature covers some designs and uses.

- “Li-Ion Battery-Supercapacitor Hybrid Storage System for a Long Lifetime, Photovoltaic-Based Wireless Sensor Network” – IEEE Transactions on Power Electronics, Vol. 27, No. 9, September 2012
- “On the Feasibility of Hybrid Battery/Ultracapacitor Energy Storage Systems for Next Generation Shipboard Power Systems” – IEEE Vehicle Power and Propulsion Conference (VPPC) 2010
- “A New Battery/UltraCapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles” – IEEE Transactions on Power Electronics, Vol. 27, No. 1, January 2012
- “Power and Life Extension of Battery-Ultracapacitor Hybrids” – IEEE Transactions on Components and Packaging Technologies, Vol. 25, No. 1, March 2002
- “Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art” – IEEE Transactions on Vehicular Technology, Vol. 59, No. 6, July 2010

Although these examples focus on mobile settings such as cars and ships, these principles could eventually extend into the stationary settings required. As a result, this is more speculative and a section to only provide information rather than being a point for recommendation.

Alternative Electrical Energy Storage

Although the above forms covered most of the current electricity storage options, there is a constant push for further development and new technologies. Therefore, although we have been able to give a distribution of the storage currently available, it is important to be aware of changes in the market. One such technology to monitor is by a company called Isentropic, which is based in United Kingdom. Isentropic (<http://www.isentropic.co.uk/>) is working on a thermal storage of electrical energy which, if successful, could have the space capabilities of electrochemical battery storage, while having efficiency and cost abilities similar to that of pumped hydro storage. Whether the technology reaches these claims or not is still yet to be seen, but is further proof of the need to monitor the changing landscape of energy storage.