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Review of Electrical Energy Storage Technologies and Systems and of their Potential for the UK

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REVIEW OF ELECTRICAL ENERGY STORAGE TECHNOLOGIES AND SYSTEMS AND OF THEIR POTENTIAL FOR THE UK

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Executive Summary

Electrical energy storage is recognised as a potentially multi-faceted technology for application in electrical power systems. It is likely to have particular value in terms of enhancing the output from intermittent renewable resources and in maintaining stability in electrical power systems, with high penetrations of Distributed Generation.

The report reviews a range of five storage technology groupings, with respect to their developmental status and potential market applicability. The technology groupings addressed are compressed air storage, batteries, flow cells, kinetic energy storage and fuel cell/electrolyser systems. Details are provided in relation to the technologies themselves, their applications potentials and the key players in the market.

The potential manufacturing, systems integration and wealth creation benefits available to UK industry are also discussed, against the backdrop of the Governmental target for 15% renewables by year 2015. The various opportunities available to UK industry are noted, even in the absence of indigenously sourced core storage technologies in themselves.

Contents

Glossary

AC	Alternating Current
AEP	American Electric Power
CAES	Compressed Air Energy Storage
DC	Direct Current
EPRI	Electric Power Research Institute
ESPC	Energy Storage & Power Consultants
HARI	Hydrogen and Renewables Integration
KESS	Kinetic Energy Storage System
LIBES	Lithium Battery Energy Storage
IFI	Innovation Funding Incentive
NATO	North Atlantic Treaty Organisation
NSRS	NATO Submarine Rescue System
O&M	Operational and Maintenance
PURE	Promoting Unst Renewable Energy
RFP	Request for Proposals
RPM	Revolutions per Minute
RPZ	Registered Power Zone
SEI	Sumitomo Electric Industries
SCS	Southern Company Services
TEPCO	Tokyo Electric Power Company
TVA	Tennessee Valley Authority
UNSW	University of New South Wales
UPS	Uninterruptible Power Supply
UPT	Urenco Power Technologies
VRB	Vanadium Redox Battery

1 Introduction

Electrical energy storage is recognised as a potentially multi-faceted technology for application in electrical power systems and where the UK possesses particular expertise in a number of areas. In more recent times, the complementarities between storage and renewables has become of particular interest, both in terms of capturing enhanced value from such essentially intermittent resources and in maintaining stability in the electrical power system. The development and application of energy storage systems and technologies therefore has the potential both to create sustainable manufacturing and employment opportunities in its own right, whilst also contributing to the Government's wider objectives, in achieving 15% of electricity supplies from eligible renewables sources, by year 2015.

Some recent work, commissioned by the DTI,[1] has identified the potential value of additional storage in the UK and also the economic hurdles that need to be overcome, for cost effective implementations. The present report has been commissioned to review the status of the current generation of storage technologies and those under development, with regard to their potential applicability on UK power systems. It addresses a range of storage technologies and systems, namely compressed air energy storage, batteries, flow cells, kinetic energy storage and fuel cell/electrolyser systems. The report describes the development status of these various systems, their potential applications and their key developers, manufacturers and suppliers. In particular, it also reviews the potential opportunities available to the UK, with particular reference to manufacturing and wealth creation benefits.

[1] Future of Energy Storage in the UK. Strbac, G. and Black, M. DTI Energy Storage Workshop, London, 13th July 2004

2 Compressed Air Energy Storage

Compressed air energy storage (CAES) plants use off-peak energy to compress and store air at high pressure (typically around 75 bar) in an airtight underground storage cavern. The pressurised air is then kept underground for use at times of peak demand. When it is needed, the stored air is released from the cavern, heated and expanded through a combustion turbine to create electrical energy. The waste heat of the exhaust is potentially captured through a recuperator before being released to the atmosphere. A basic schematic of the process is shown in Figure 2.1.

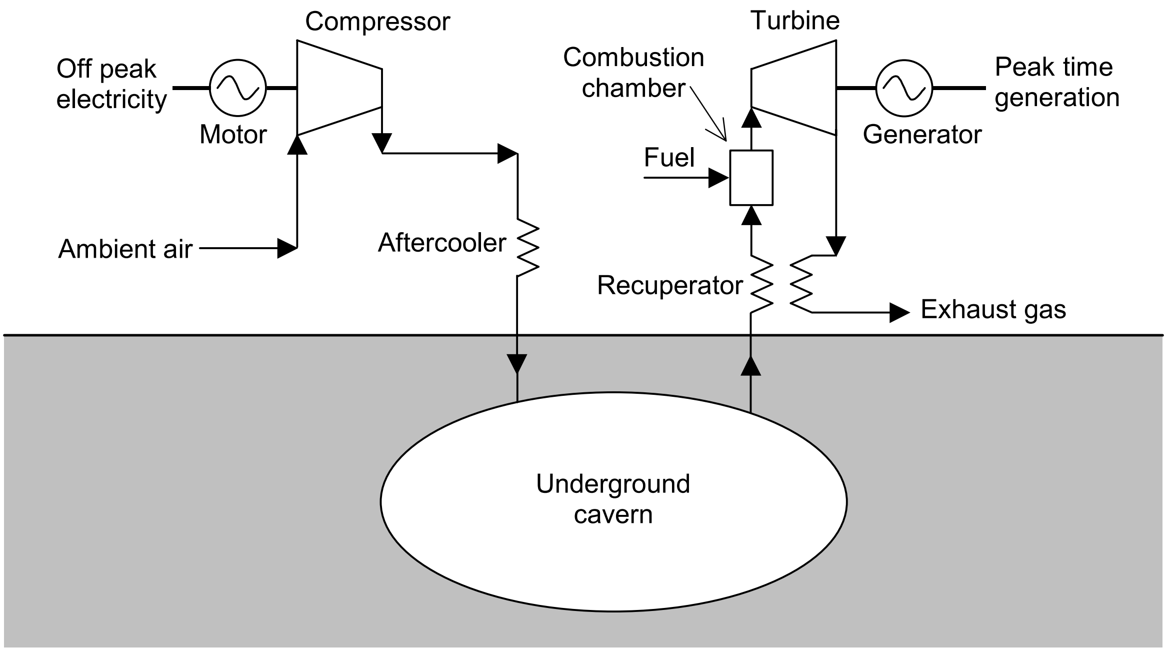

Figure 2.1 Schematic of a Compressed Air Energy Storage System

The siting of CAES plant requires favourable geology for the storage reservoir as well as a suitable location near transmission lines and fuel supplies. Potential sites for underground storage are grouped into three categories:

- rock caverns created by excavating comparatively hard and impervious rock formations;
- salt caverns created by solution or dry mining of salt formations;
- porous media reservoirs made by water bearing aquifers or depleted gas or oil fields e.g., sandstone, fissured limestone.

Typical ratings for a CAES system are in the range 50 to 300 MW, much higher than for other storage technologies other than pumped hydro. The storage period is also longer than other storage methods since the losses are very small; a CAES system can be used to store energy for more than a year. Capital costs for CAES facilities vary depending on the type of underground storage but are typically in the range from $500 to $660 per kW[2].

One of the principal drawbacks of CAES is its reliance on favourable geological structures which limits the potential of this storage method. As a result, current research is focused on the development of systems with fabricated storage tanks. The scales proposed are relatively small compared to underground CAES systems. Further details on small scale CAES are provided in section 2.2.

2.1 CAES Installations

At present there are only two CAES plants in operation in the world, although several others are planned. A brief overview of the existing and planned facilities is provided in sections 2.1.1 to 2.1.3 below.

2.1.1 Huntorf Plant[3]

The world's first commercial CAES facility, located in Huntorf in Germany, is operated by E.ON. It was commissioned in 1978 and has been running for more than 25 years. The CAES plant's main roles are as an emergency reserve in case of unplanned failure of other power plants and as an alternative option to purchasing expensive peak load from outside suppliers.

The storage facility comprises two underground salt caverns with a total storage volume of 310,000 m^3. The depth of the caverns is more than 600 m which ensures the stability of the air for several months' storage, as well as guaranteeing the specified maximum pressure of 100 bar.

Compression is achieved using an electrically driven 60 MW air compressor and the system is charged over an eight hour period. The plant is able to deliver 290 MW for two hours. Since its installation in 1978, the plant has accumulated over 7,000 starts and has showed 90% availability and 99% starting reliability.

2.1.2 McIntosh Plant[4]

The second commercial CAES facility was built in 1991 at McIntosh, Alabama. It incorporated several improvements over the Huntorf plant, including a waste heat recovery system that reduces the fuel usage by around 25%. The majority of the funding for the $65 million plant was

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2 Energy Storage Options for Central Illinois; Makansi, J, van der Linden, S and Schien, K; EESAT 2003, San Francisco, 27-29 October 2003

3 Huntorf CAES: More than 20 Years of Successful Operation; Crotogino, F, Scharf, R and Mohmeyer, K; SMRI Spring 2001 Meeting, Orlando, 15-18 April 2001

4 CAES Development Company web site: www.caes.net/mcintosh.html

provided by the Alabama Electric Co-operative, with support from the Electric Power Research Institute (EPRI) and the National Rural Electric Co-operative Association.

The system has a rated capacity of 100 MW from a salt cavern more than 450 m underground and with a storage volume of over 500,000M^3. When the facility is fully charged the air pressure is 74 bar and at full discharge cavern air pressure is 45 bar. The key function of the facility is for peak shaving and the system can supply power for 26 hours.

2.1.3 Planned CAES Facilities[5]

There are several CAES plants planned or under development. These include:

- *Norton, Ohio*. This is a 2,700 MW plant jointly developed by CAES Development Company and Alstom Power. A 670 m deep inactive limestone mine is being used as the storage vessel. It is intended that the facility will generate wholesale electric power for sale to utilities and marketing companies for use during times of peak energy demand.

- *Markham, Texas*. This plant is configured as 540 MW (4 x 135 MW) of compressed air energy storage and is being developed jointly by Ridge Energy Storage and El Paso Energy. A salt cavern is being used as the storage vessel. The projected start up date for the facility is 2005.

2.2 Small Scale CAES[6]

Energy Storage and Power Consultants (ESPC) have conducted extensive engineering studies into various alternatives for above ground compressed air storage. On the basis of capital cost, an arrangement utilising subsurface high pressure vessels/piping was selected for further development. This development work has been carried out jointly with EPRI with support from manufacturers.

The small scale CAES system utilises Allison combustion turbines with outputs of 8 to 12 MW. In order to reduce the volume of the storage vessels/piping, significantly higher storage pressures (typically 100 to 140 bar) are used compared with underground storage facilities. The capital cost of the plant is approximately $550 per kW and it can provide power for 3 to 5 hours.

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[5] The Commercial World of Energy Storage: A Review of Operating Facilities (under construction or planed); van der Linden, S; 1st Annual Conference of the Energy Storage Council, 3 March 2003

[6] New Compressed Air Energy Storage Concept Can Improve the Profitability of Existing Simple Cycle, Combined Cycle, Wind Energy, and Landfill Gas Combustion Turbine-based Power Plants; Nakhamkin, M et al; EESAT 2003, San Francisco, 27-29 October 2003

The principle behind small scale fabricated compressed air storage systems is the same as that for underground CAES facilities; i.e. they use off-peak energy to compress air and store it for expansion during peak demand periods. The concept would be particularly effective if integrated with renewable sources as it allows collection and storage of the renewable energy when it is available and releasing it when the energy is needed at premium prices. ESPC have carried out extensive studies on the integration of wind power and landfill gas with small scale CAES but, as yet, no field trials have been carried out.

3 Battery Energy Storage Systems

The oldest and most established way of storing electricity is in the form of chemical energy in batteries. A battery comprises of one or more electrochemical cells and each cell consists of a liquid, paste, or solid electrolyte together with a positive electrode and a negative electrode. During discharge, electrochemical reactions occur at the two electrodes generating a flow of electrons through an external circuit. The reactions are reversible, allowing the battery to be recharged by applying an external voltage across the electrodes.

Battery systems range from mature and reliable technologies, such as lead acid, which have been proven and developed over many years, to various newer designs which are at different stages of development; these include sodium sulphur and sodium nickel chloride. In recent years, new developments have been driven by the demands of consumer electronics, portable and transport applications, although there is increasing interest in the use of large scale batteries for utility energy storage applications.

Electrochemistries that are either in use and/or potentially suitable for utility scale battery energy storage applications include lead acid, nickel cadmium, sodium sulphur, sodium nickel chloride and lithium ion. Sections 3.1 to 3.5 below provide an overview of the developmental status and experience base of these five battery technologies for utility scale storage applications. A summary of the performance characteristics of each system is given in Table 3.1..

Table 3.1 Comparison of Different Battery Energy Storage Systems

	Lead acid	Nickel cadmium	Sodium sulphur	Lithium ion	Sodium nickel chloride
Achieved/demonstrated upper limit power	Multiple tens of MW	Tens of MW	MW scale	Tens of kW	Tens/low hundreds of kW
Specific energy (Wh/kg)	35 to 50	75	150 to 240	150 to 200	125
Specific power (W/kg)	75 to 300	150 to 300	90 to 230	200 to 315	130 to 160
Cycle life (cycles)	500 to 1500	2,500	2,500	1,000 to 10,000+	2,500+
Charge/discharge energy efficiency (%)	~80	~70	up to 90	~95	~90
Self discharge	2 to 5% per month	5 to 20% per month	#	~1% per month	#

Although there is no self discharge reaction, there is a parasitic loss associated with maintaining the battery temperature.

3.1 Lead Acid Batteries

In its basic form, the lead acid battery consists of a negative electrode made from lead, a positive electrode made from lead dioxide and a separator to electrically isolate the positive and negative electrodes. The electrolyte is dilute sulphuric acid, which provides the sulphate ions for the discharge reactions. There are several types of lead acid battery: the flooded battery, which requires regular topping up with distilled water; the sealed maintenance-free battery, which has a gelled or absorbed electrolyte, and the valve regulated lead acid battery.

Lead acid batteries have been used for more than 130 years in many different applications and they are still the most widely used rechargeable electrochemical device. Continual developments of the technology have resulted in constant improvements regarding the cell capabilities. As a result, modern lead acid batteries have the advantage of being low cost, with high reliability.

Lead acid technology is also being continually improved to reduce the need for maintenance. Indeed, its energy density has been increased by over 50% since the 1950s. However, its energy density remains low due to the inherent high density of lead, which results in a high total mass in large energy storage requirements. Lead acid batteries also have poor low temperature performance and therefore require a thermal management system. However, with good battery management and a well optimised operational regime, these systems have been shown to be financially competitive.

Table 3.2 Selected Lead Acid Battery Energy Storage Installations[7]

Plant name and location	Year of installation	Rated energy (MWh)	Rated power (MW)	Application
BEWAG, Berlin	1986	8.5	8.5	Spinning reserve Frequency control
Crescent, North Carolina	1987	0.5	0.5	Peak demand reduction
Chino, California	1988	40	10	Spinning reserve Load levelling
PREPA, Puerto Rico	1994	14	20	Spinning reserve Frequency control
Vernon, California	1995	4.5	3	Security of supply Power quality
Metlakatla, Alaska	1997	1.4	1	Stabilisation of island grid
ESCAR, Madrid	Early 1990s	4	1	Load levelling

7 Electricity Storage Association: www.electricitystorage.org

Herne-Sodingen, Germany	Late 1990s	1.2	1.2	Peak shaving Power quality

Lead acid batteries have been used in a number of commercial and large scale energy management applications. These have generally been bespoke systems. Table 3.2 shows the key features of selected installations. There are still very few installations in Europe; these include:

- The BEWAG plant in Berlin was constructed in 1986 prior to the reunification of Germany when the western half of the city was effectively an "electrical island" in the East. The main function of the energy storage system is for spinning reserve and frequency control.

- The ESCAR Battery Storage System at the Iberdrola Technology Demonstration Centre in Madrid is used for load levelling, with 1 MW power and 4 MWh energy. For peak reserve it can provide 1.2 MW of power and 2 MWh of energy. The facility is designed to be used for both these applications. It is the pioneer in use of load levelling and the European leader in terms of power and energy storage.

- The Energie-Park in Herne-Sodingen, Germany, has a multifunctional high power lead acid battery which is a 1.2 MW / 1 hour rated system and has a 10 hour capacity of 1380 Ah. The energy storage system is used for peak load shaving, improvement of power reliability and improvement of power quality. Peak load shaving involves the use of regeneratively produced energy, stored in a battery for peak load periods. This system is an open battery and requires a supply of air and water.

Packaged lead acid battery systems are available for power quality applications and uninterruptible power supply (UPS) systems. For example, S&C Electric Company produce the PureWave UPS™ System[8] that provides power protection to entire facilities served by a single source, and protects power sensitive equipment from the effects of power disturbances. The system is designed to support full loads for a minimum of 30 seconds and a maximum of 60 seconds for partial load conditions. The medium-voltage PureWave UPS™ System can deliver a maximum of 2.5 MVA (per container) of clean power and can switch critical loads from the utility service to the system's standby battery energy source in 2 to 4 milliseconds. Up to eight 2.5 MVA containers can be connected in parallel to protect larger loads up to 20 MVA. Large scale installations of the PureWave UPS™ System include semiconductor manufacturing facilities and data centres.

[8] PureWave UPS™ System: www.sandc.com/products/puurewave

3.2 Nickel Cadmium Batteries

Nickel Cadmium (NiCd) battery systems rank alongside lead-acid systems in terms of their maturity, with a pedigree dating back some one hundred years. The technology was previously favoured for power tools and such portable devices as mobile telephones and laptops, but has effectively been displaced from these markets by other electro-chemistries, over the past decade. The robust nature of the technology, combined with its energy density advantage over lead-acid does however lend itself to aircraft applications and to a certain extent, electric vehicles. It is also at the heart of the flagship Golden Valley battery energy storage system in Alaska, as is discussed later.

The technology itself exists in two principal variants, namely the pocket plate and sintered plate designs. In the pocket plate design the active material is held between steel plates in what is usually a vented cell configuration. The more expensive sintered plate design employs various substances as the current collector, with the active material matrix sintered onto these. The manufacturing process itself is inherently more expensive than in lead-acid batteries, which accounts for a substantial part of the cost differential.

Cadmium is a toxic heavy metal and there are concerns relating to the possible environmental hazards associated with the disposal of NiCd batteries. In November 2003, the European Commission adopted a proposal for a new battery Directive which includes recycling targets of 75% for NiCd batteries[9]. However, the possibility of a total ban on rechargeable batteries made from nickel cadmium still remains and hence the long term viability and availability of NiCd batteries continues to be uncertain. NiCd batteries can also suffer from “memory effect”, where the batteries will only take full charge after a series of full discharges. Proper battery management procedures can help to mitigate this effect.

NiCd batteries are frequently used in preference to lead-acid batteries in applications where very high reliability is required, e.g. emergency lighting, UPS, telecoms, generator starting etc. The batteries have very low maintenance requirements here, which provide a significant advantage over lead-acid.

The NiCd system has also achieved significant prominence in terms of its application in the “world’s largest (most powerful) battery”, at Golden Valley, Fairbanks, Alaska[10]. The system here provides critical spinning reserve functionality in what is effectively an “electrical island”. It comprises four battery strings, each of 3,440 cells, with a string voltage

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[9] Proposal for a Directive on Batteries and Accumulators and Spent Batteries and Accumulators COM(2003), 21 November 2003

[10] The World’s Most Powerful, BESS, is Online and Working in Alaska. DeVries, T., Golden Valley Association, EESAT 2003, San Francisco, 27-29 October 2003.

of 5,200 volts. The system is rated at 27 MW for 15 minutes, 40 MW for 7 minutes and with an ultimate 46 MVA limitation imposed by the power converter. The batteries are expected to perform 100 complete and 500 partial discharges in the system's 20 year design life. Total project cost was some $35M, with the Golden Valley utility assessing the project as "no more risky than any equivalent sub-station project".

3.3 Sodium Sulphur

The sodium-sulphur battery consists of liquid sulphur as the negative electrode and liquid sodium as the positive electrode. A solid electrolyte of β-alumina separates both electrodes. The battery operates at a temperature of 300 to 350°C.

Batteries that operate at elevated temperatures exhibit improved performance compared with ambient temperature batteries, although they do require insulating to prevent rapid heat loss. Consequently a heat source is required, which uses the battery's own stored energy, partially reducing the battery performance. No self-discharge occurs though, resulting in an overall efficiency as high as 90% including heat losses.

The sodium sulphur battery was originally developed for vehicle drives and, compared to the lead acid battery, has the advantage of lower weight and smaller external dimensions. There has only been limited interest in the use of sodium sulphur for stationary applications with most of the research and development work carried out jointly by Tokyo Electric Power Company (TEPCO) and NGK Insulators in Japan. They have been developing a sodium sulphur energy storage system to provide load levelling since 1984. TEPCO launched direct sales of sodium sulphur battery systems in April 2002 and, in parallel, NGK committed to commercial scale production facilities with an annual production capacity of 65 MW. By the end of September 2003, 16 commercial systems had been commissioned in Japan with an accumulated capacity exceeding 15 MW[11]. NGK have recently commissioned what is claimed to be the world's largest (capacity) battery energy storage system (8MW/58MWh) at a Hitachi plant in Japan.[12]

American Electric Power is currently conducting the first grid-connected demonstration of sodium sulphur technology in the United States at a corporate office complex in Ohio[13]. The system is rated at 100 kW for peak shaving or load levelling over about seven hours and up to 500 kW for short term power quality mitigation. It has been operating in a

[11] Commercial Deployment of the NAS Battery in Japan; Takami, H and Takayama, T; EESAT 2003, San Francisco, 27-29 October 2003

[12] The NaS Battery System for Utility Scale Energy Storage. NGK Product Information, 2004.

[13] Performance and Economic Analysis of the NaS Battery Demonstration at American Electric Power; Norris, L et al; EESAT 2003, San Francisco, 27-29 October 2003

combined peak shaving/power quality mode since its start up and acceptance testing in September 2002. The project is being conducted in collaboration with EPRI, the US Department of Energy, TEPCO, NGK and ABB.

Current price levels are around $250 per kWh and are expected to fall to around $140 per kWh as production volumes increase.

3.4 Sodium Nickel Chloride

The sodium nickel chloride battery is better known as the ZEBRA battery. It is a high temperature system that uses nickel chloride as its positive electrode and has the ability to operate across a broad temperature range (-40°C to +70°C) without cooling. Advantages compared to sodium sulphur batteries are that it is able to withstand limited overcharge and discharge, has potentially better safety characteristics and a higher cell voltage. The disadvantages with respect to sodium sulphur are its lower energy and power density, although the former is still a considerable improvement over lead acid technology.

The ZEBRA system was extensively developed by the British company, Beta R&D, prior to the rights to the technology being acquired by MES, the Swiss automotive and white goods component manufacturer, in 1999. MES's acquisition of the technology has resulted in much of Beta R&D's pilot manufacturing plant being re-located to MES's factory in Lugano, Switzerland, where the MES is tooling up for mass production, principally for the electric and hybrid vehicle markets.

Beta R&D became an independent company in April 2003 following a management buy out. The company remains the exclusive agent for the sale of ZEBRA batteries in Europe and has therefore retained its links with MES. At present Beta R&D is developing a high power version of the ZEBRA battery for hybrid electric vehicles, a high energy version for storage of renewable energy and a load-levelling battery for industrial applications[14]. The application of the ZEBRA battery in the new NATO Submarine Rescue System (NSRS) has also recently been announced.[15]

3.5 Lithium Ion Batteries

The first commercial lithium ion batteries were produced by Sony in 1990. Since then, improved material developments have led to vast improvements in energy density terms from figures of 75 Wh/kg to 175 Wh/kg and increased cycle lives as high as 20,000 cycles.

In Japan, the Lithium Battery Energy Storage Technology (LIBES) Association has been evaluating lithium ion batteries as a means of providing distributed energy storage systems since 1992, in parallel with

[14] Beta R&D Ltd web site: www.betard.co.uk
[15] The Engineer, 10th – 23rd September 2004

developing lithium ion batteries for electric vehicle applications. The aim has been to develop systems, which would offer domestic and small commercial businesses stand by power and peak shaving potential. The LIBES programme has produced 3 kW demonstration modules with energy densities as high as 300 Wh/kg and cycle lives of up to 1,000 cycles but, as yet, no commercial product has emerged.

Kyushu Electric Power and Mitsubishi Heavy Industries have been pursuing joint research on large scale lithium ion battery development and are working to create an electric power storage system focused on extending the life of lithium batteries[16]. Their prototype 24 kWh unit has an output of 3 kW for 8 hours and has been tested in load levelling and peak shaving modes and has attained a system efficiency of 86%. Future development plans include creating a larger system by connecting 24 kWh systems in parallel and adjusting the system for a three phase load.

In the United States, the Department of Energy has sponsored a project by SAFT and SatCon Power Systems to design and construct two 100 kW / 1 minute lithium ion battery energy storage system for use in providing power quality for grid-connected microturbines[17]. Both units are being tested at utility partner sites, one at Southern Company Services (SCS) and the other at American Electric Power (AEP). The demonstration at SCS uses the energy storage to supplement distributed power generation via microturbines and to provide load-following capability. The system installed at AEP using the battery as a UPS. To date, the systems have been online at the two utility test facilities for over 2,400 hours. After completion of the utilities' laboratory testing, both utility companies will install the units at customer sites where their performance will continue to be monitored.

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[16] Development of 24 kWh Power Storage System Applying Li-Ion Batteries; Shibata, H et al; EESAT 2003, San Francisco, 27-29 October 2003

[17] Development and Manufacturing of Two 100 kW / 1 minute Li-ion Battery Systems for Electricity Storage; Oweis, S et al; EESAT 2003, San Francisco, 27-29 October 2003

4 Electrochemical Flow Cell Systems

Electrochemical flow cell systems, also known as redox flow cells, convert electrical energy into chemical potential energy by means of a reversible electrochemical reaction between two liquid electrolyte solutions. In contrast with conventional batteries, redox flow cells store energy in the electrolyte solutions. Therefore, the power and energy ratings are independent, with the storage capacity determined by the quantity of electrolyte used and the power rating determined by the active area of the cell stack.

A redox flow cell system is made up of a number of electrochemical cells. Each cell has two compartments, one for each electrolyte, physically separated by an ion-exchange membrane. The electrolytes are stored in two tanks and are pumped through the cell stack across a membrane where one form of the electrolyte is electrochemically oxidised and the other is electrochemically reduced. This creates a current that is collected by electrodes and made available to the external circuit. The reaction is reversible allowing the battery to be charged, discharged and recharged. A simplified schematic of a redox flow cell energy storage system is shown in Figure 4.1.

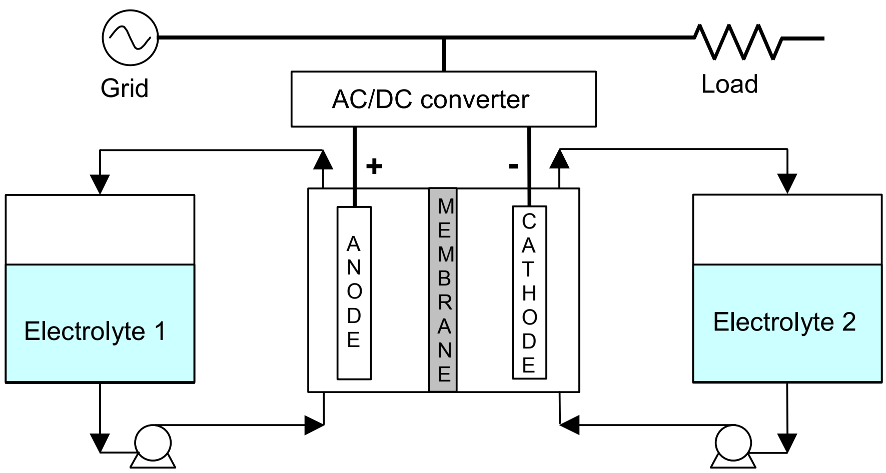

Figure 4.1 Schematic of a Redox Flow Cell Energy Storage System

At the present time there are three principal electrochemistries of interest: vanadium redox, zinc bromine and polysulphide bromide (Regenesys™). The current status of these technologies is discussed in sections 4.1 to 4.3 below. A summary of the performance characteristics of each energy storage system is given in Table 4.1..

Table 4.1 Comparison of Redox Flow Cell Energy Storage Systems

	Vanadium	Zinc bromine	Regenesys™
Size range (MWh)	0.5 to 5	0.05 to 1	up to 120
Energy density (Wh/litre)	16 to 33	up to 60	
Cycle efficiency (%)	78 to 80	65 to 75	60 to 75
Cycle life (cycles)	> 12,000	> 2,000	
Unit design lifetime (years)	5 to 10	5 to 10	15

4.1 Vanadium Redox Battery

The vanadium redox battery (VRB) employs the V2/V3 and V4/V5 redox couples in sulphuric acid as the negative and positive electrolytes respectively. The reactions that occur in the battery during charging and discharging can be expressed simply by the following equations:

Positive electrode: $$V^{4+} \underset{\text{Discharge}}{\overset{\text{Charge}}{\longleftrightarrow}} V^{5+} + e^-$$

Negative electrode: $$V^{3+} + e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\longleftrightarrow}} V^{2+}$$

Vanadium redox batteries are suitable for a wide range of energy storage applications for electricity utilities and industrial end-users. These include enhanced power quality, uninterruptible power supplies, peak shaving, increased security of supply and integration with renewable energy systems. The majority of development work has focused on stationary applications due to the relatively low energy density of vanadium redox batteries.

The vanadium redox battery was developed and patented by the University of New South Wales (UNSW) in the early 1980s. In September 1998, all patents, technology, know-how and licences associated with the vanadium redox battery were bought by Pinnacle VRB and the company subsequently licensed the technology to Vanteck Technology Corporation in Canada and Sumitomo Electric Industries (SEI) in Japan. In December 2001, Vanteck completed the take-over of Pinnacle VRB, acquiring the world-wide rights to the VRB technology. In January 2003, Vanteck changed its name to VRB Power Systems Incorporated.

A summary of the activities and installations that have been undertaken by VRB Power and SEI are provided below. Other companies that are pursuing VRB energy storage development programmes include

Magnam Technologies, RE-fuel Technology and the Cellennium Company.

VRB Power Systems Inc.[18]

VRB Power has developed the Vanadium Energy Storage System which is a proprietary advancement of the basic VRB technology pioneered by UNSW. The power electronics are supplied by the TSI Division of Eskom and the cell stacks and electrolyte tanks are supplied by SEI. VRB Power has installed three energy storage systems to date and these are summarised in Table 4.2.

Table 4.2 Energy Storage Systems Supplied by VRB Power

Customer	Basic Specification	Application	Start date
Eskom	250 kW x 2 hours	Demonstration unit at University of Stellenbosch	September 2001
Pacificorp	250 kW x 8 hours	Peak power capacity and end of line voltage support	March 2004
Hydro Tasmania	200 kW x 4 hours	Three way hybrid with wind turbines and diesel generator	November 2003

Sumitomo Electric Industries Ltd.

SEI has been involved in the development of redox flow cells since 1985 in collaboration with Kansai Electric Power. They have successfully built demonstration scale units for grid load levelling applications and have been building and installing commercial scale units in Japan since 2001. A summary of the systems supplied by SEI since 2001 is given in Table. The system for Tottori Sanyo Electric is operating at a large liquid crystal manufacturing plant as a combination of UPS for voltage sag compensation and a peak shaver to reduce peak load. It has successfully compensated for more than 40 voltage sag events that have occurred since installation[19].

Table 4.3 VRB Energy Storage Systems Supplied by SEI since 2001[20]

Customer	Basic Specification	Application	Operational start date
Institute of Applied Energy	AC 170 kW x 6 hours	Stabilisation of wind turbine output	March 2001
Tottori Sanyo Electric	AC 3 MW x 1.5 sec.	UPS	April 2001

[18] VRB Power Systems web site: www.vrbpower.com
[19] Recent Progress in Vanadium Redox Flow Battery; Emura, K; EESAT 2003, San Francisco, 27-29 October 2003
[20] Sumitomo Electric Industries web site: www.sei.co.jp

	AC 1.5 MW x 1 hour	Peak shaving	
Obayashi Corporation	DC 30 kW x 8 hours	Hybrid with photovoltaic cells	April 2001
Kwansei Gakuin University	AC 500 kW x10 hours	Peak shaving	November 200l
Centro Elettrotecnico Sperimentale Italiano	AC 42 kW x 2 hours	Peak shaving	November 2001

4.2 Zinc Bromine Battery

The zinc bromine battery consists of a zinc negative electrode and a bromine positive electrode separated by a microporous separator. Solutions of zinc and a complex bromine compound are circulated through the two compartments of the cell from two separate reservoirs. During charge, zinc is electroplated on the cathode and bromine is evolved at the anode; this is stored as a chemically complexed organic phase at the bottom of the positive electrolyte tank. A third pump is used for recirculation of the organic phase during the discharge cycle. On discharge, the zinc is oxidised to zinc ions and bromine is reduced to bromide ions.

The reactions that occur at the two electrodes during charge and discharge can be expressed simply by the following equations:

Positive electrode: $$2Br^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Br_2\,(aq) + 2e^-$$

Negative electrode: $$Zn^{2+} + 2e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Zn$$

Zinc bromine batteries are suitable for a range of applications with discharge times ranging from seconds up to several hours. The primary focus of development and demonstration projects, however, is for on-grid utility applications for load levelling and renewable energy system optimisation.

The zinc bromine battery was first developed by Exxon in the early 1970s. A number of multi-kWh units have been demonstrated and, in 1991, Meidisha demonstrated a 1 MW/4 MWh zinc bromine battery at Kyushu Electric Power Company[21]. At the current time, the only company that is actively developing and supplying zinc bromine batteries is ZBB Energy Corporation (ZBB). The company was established in 1982 and over the last 20 years has developed or acquired the intellectual property for the zinc bromine battery. ZBB's

[21] Electricity Storage Association web site: www.energystorage.org

headquarters and production facilities are in the United States and, in addition, the company maintains research and development and regional marketing facilities in Perth, Western Australia.

ZBB has spent over $40 million on development and owns some 45 patents covering all aspects of the technology. The zinc bromine energy storage system is now in the first stages of commercialisation and the company's baseline turnkey product is the F2500, a fully containerised 500 kWh (250 kW x 2 hours) grid-interactive storage system[22]. In addition, it can supply individual 50 kWh modules for renewable energy applications. Key demonstration units installed by ZBB in recent years are summarised in Table 4.4.

[22] ZBB Energy Corporation web site: www.zbbenergy.com

Table 4.4 Zinc Bromine Energy Storage Systems Supplied by ZBB Energy Corporation

Customer	Basic Specification	Application	Installation date
Detroit Edison	400 kWh	Peak shaving and voltage imbalance	June 2001
United Energy, Melbourne	200 kWh	Demonstration unit for network storage applications	November 2001
Australian Inland Energy	500 kWh	Hybrid with photovoltaic cells	June 2002
PowerLight Corporation	2 x 50 kWh	Hybrid with photovoltaic cells	November 2003
Pacific Gas and Electric Company	2 MWh	Peak power capacity (substation upgrade deferral)	October 2005

4.3 Polysulphide Bromide (Regenesys™)

The Regenesys™ system has previously been developed over the past twelve years by RWE Innogy and its predecessor companies (Innogy and National Power). The system has been marketed as a grid-connected utility scale storage system, for power ratings in excess of 5MWe. Notwithstanding the significant scale-up of and commitment to Regenesys™ related activities, RWE Innogy announced in December 2003 that it would no longer be funding the technology's development and subsequent commercialisation. It has since announced (September 2004) the sale of an exclusive five year licence on the Regenesys™ intellectual property and related physical assets to VRB Power Systems, for the sum of $1.3M[23].

Regenesys™ utilises the reversible electro-chemical reaction between two salt solution electrolytes, namely sodium bromide and sodium polysulphide, viz:-

$$3NaBr \quad + \quad Na_2S_4 \Leftrightarrow 2Na_2S_2 \quad + \quad NaBr_3$$

During the charging cycle, the electro-chemical reaction proceeds from left to right; during the discharge cycle the reaction proceeds from right to left.

Initial pilot plant activities were conducted at RWE Innogy's Aberthaw power station in South Wales and progressed to the construction of two initial demonstration plant, each rated at 12 MWe/120 MWh capacity. The first of these is adjacent to RWE Innogy's Little Barford power station in Cambridgeshire. The Little Barford plant was regarded as the first

[23] VRB Power Acquires Regenesys Electricity Storage Technology, Power Engineering International, 27th September 2004.

complete integrated demonstration plant for the technology and an essential demonstration and proving facility. It was however never fully commissioned.

The second demonstration plant is located at the Tennessee Valley Authority's (TVA's) facility in Columbus, Mississippi. It is understood that the majority of the civil works have been completed at this plant, although none of the actual electro-chemical cell modules had been installed. TVA have recently issued an RFP[24], soliciting proposals for the completion of the plant in one form or another.

5 Kinetic Energy Storage Systems (Flywheel Storage)

Kinetic energy storage systems rely for their operation on the stored energy in a rotating mass, with its conversion from and to electrical energy via a motor/generator set. Whilst flywheels themselves have been an established part of reciprocating engine design since the advent of the first steam engines, the present section is principally concerned with their application in electrical power systems.

Such kinetic energy storage systems (or flywheel storage systems, as they are more commonly known) tend to fall into two discrete categories, namely conventional steel rotor systems or advanced composite machines. The following sections summarise some of the salient features of the design of such systems and provide details of the sorts of units available and of their applications domain.

5.1 Component Technologies

A kinetic energy storage system comprises the following essential component technologies.

The **kinetic energy store** (flywheel) itself. Important design features include materials selection and fabrication, component geometry, rotor dynamics and speed. The overall objective is to achieve maximum storage of rotational kinetic energy within given constraints of volume envelope, mass, cost and safety.

A **containment system,** together with its ancillary services, will also usually be required, in all but a very few instances. The primary function of the containment system in normal operation is to provide a high

[24] Requesting Proposals for Completing TVA's Regenesys Plant in Columbus, Mississippi, Tennessee Valley Authority, 15th June 2004

vacuum environment (10^{-3} to 10^{-5} torr) to minimize windage losses and to protect the rotor assembly from external disturbances. In a failure situation, the containment provides a secondary function, of absorbing the energy of the exploding rotor and containing the debris within a defined volume envelope.

Bearing assemblies are another of the essential sub-assemblies and ideally provide a very low loss support mechanism for the flywheel rotor, in order to reduce losses of kinetic energy over extended periods of operation.

Finally, a **power conversion and control system** must be provided, both to import power during charging and to accelerate the rotor up to speed and vice versa, during discharge. The power conversion system must cope with the varying speed of the rotor sub-assembly and be fully compatible with the external electrical interface.

5.2 Kinetic Energy Storage Systems and Suppliers

Kinetic energy storage systems are either under development or available on a commercial basis from some dozen plus organisations. Systems range from relatively conventional, low speed steel rotor, series produced units, through bespoke systems, designed for specific end use applications, to high speed units, employing state-of-the-art composite materials construction. The present section provides further information on some of these systems and their designs.

5.2.1 Conventional Steel Rotor Systems

Conventional steel rotor based systems represent the well established commercial implementation of flywheel energy storage and have been available on the market for a numbers of years. The leading commercial suppliers are Piller (Germany), Active Power (US), Satcon (US) and Caterpillar (US), with the latter packaging Active Power's flywheel technology into its own proprietary UPS system. The systems are principally marketed for and sell into relatively short term (circa 10 to 100 second) medium/high load UPS ride-through type applications, power quality enhancements and short-term load levelling applications. The systems' high levels of reliability, overall technological maturity, tolerance to (deep) cyclic loading and low operational and maintenance (O&M) requirements are all highly attractive and important features in such applications, rather than their absolute performance, per se. Systems may be marketed either as "straight" DC systems, with the customer then responsible for the selection and incorporation of any AC power conversion system that may be required, or as "complete" UPS systems, which may be directly incorporated into electrical power networks.

5.2.2 High Speed Composite Kinetic Energy Storage Systems

Much of the current research and developmental effort in relation to flywheel energy storage systems is directed towards high speed machines, running at tens of thousands of RPM and utilising state-of-the art composite materials technology. The high directional strength properties of such composites, in combination with their relatively low densities allows the designer consider freedom in optimising the overall flywheel configuration and hence its specific energy and specific power. Units have already been supplied on a commercial basis by Urenco Power Technologies (UPT) and with further systems being developed by AFS-Trinity, Beacon Power, Piller and others. Further details on some of these systems are provided below.

5.2.2.1 Urenco Power Technologies

The UPT Kinetic Energy Storage System (KESS) is based on its Urenco parent organisation's high speed gas centrifuge Uranium enrichment technology. Although often loosely referred to as a flywheel energy storage system the UPT system is in fact based on a cylindrical rotor/drum configuration, which provides advantages in terms of ultimate failure mode and footprint energy density. The UPT unit is rated in its standard form at 200 kWe (for traction markets) and 250 kWe (for UPS markets) with 15 MJ (4.2 kWh) of stored energy, of which 12 MJ (3.3 kWh) is extractable. Several dozen applications are believed to have been implemented to date, including those in relation to trackside voltage support and wind turbine smoothing[25]. However, the company's future seems somewhat uncertain at time of writing (August 2004), due to the decision by its Urenco parent company, May 2004, to cease funding the development of the technology.

5.2.2.2 AFS-Trinity

AFS-Trinity is developing its M3 system, which offers 100 kWe output over 15 seconds, with a peak rating of 200 kWe and 0.42 kWh of usable stored energy[26]. The system is claimed to offer 95% one way and 90% round trip efficiencies at 110 kWe, with 700 Watt of parasitic losses. System mass is stated to be less than 500 kg, with a footprint of $0.35m^2$.

5.2.2.3 Beacon Power

Beacon Power has offered 2 and 6 kWh capacity products, each rated at 2 kWe output, for the telecommunications market, over the past 2 to 3 years. The units are approximately 0.6 metre diameter and 1 metre in height, with the nominal 70 kg. flywheel mass rotating at up to 20,000

[25] UPT KESS, the ultimate energy management system. UPT Product Literature, December 2003

[26] Successes and Opportunities in High Speed Flywheel Development, Bender, D.A., AFS-Trinity, EESAT 2003, San Francisco, October 2003

RPM. The company has also marketed UPT's products in the US and is developing its own 25 kWh/250 kWe unit[27].

5.2.2.4 Piller

Piller is in the early stages of developing its Dynastore 2 MWe output, 11 kWh usable output flywheel storage system, for power quality related applications[28]. Piller is responsible for the overall design and integration of the system and is co-ordinating the activities of nine industrial and academic partners, under a German Government sponsored project. A commercial product is anticipated to be available in some two to three years time.

5.3 Flywheel Storage Overview

The sections above have demonstrated that kinetic energy storage systems are already commercially available and under development, to satisfy a range of market requirements. Their emphasis is principally on high power/short duration applications (eg 100s of kW/tens of seconds), with their ability to withstand repeated cyclic loading within this operational regime.

Within the utility and related power distribution systems context, their principal applications domain to date has been in relation to power quality and UPS, although with the majority of installations to date being on customers' premises, as opposed to power utilities' distribution systems. Such systems may often be implemented in a hybrid configuration with stand-by diesel generators, with the complete system providing an uninterrupted ride-through capability, in the event of loss of utility supply. UPT has recently demonstrated the application of kinetic energy storage to the smoothing of the output of wind turbine systems and the associated stabilisation of small scale island power supply networks.

The rail traction industry represents another significant and high added value application for flywheel storage, particularly for trackside voltage support. This application could well represent a significant growth area in the years ahead, with the prevalence of increasing numbers of larger and heavier train sets being imposed on existing infra-structures.

6 Hydrogen Based Energy Storage Systems

[27] www.beaconpower.com

[28] DYNASTORE – A Flywheel Energy Storage System for Power Quality Applications in the 10kWh Class. Darrelmann, H et al, EESAT 2003, San Francisco, Oct 2003.

Hydrogen based energy storage systems are receiving increasing attention at the present time, particularly in relation to their integration with renewable power sources. Their essential elements comprise an electrolyser unit, to convert the electrical energy input into hydrogen, the hydrogen storage system itself and a hydrogen energy conversion system, to convert the stored chemical energy in the hydrogen back to electrical energy. There is a strong technical preference for this latter element to be a fuel cell system, in order to capitalise on its high energy conversion efficiency, although this does not preclude the use of hydrogen burning internal combustion engines. Figure 6.1 provides a diagrammatic representation of such a system.

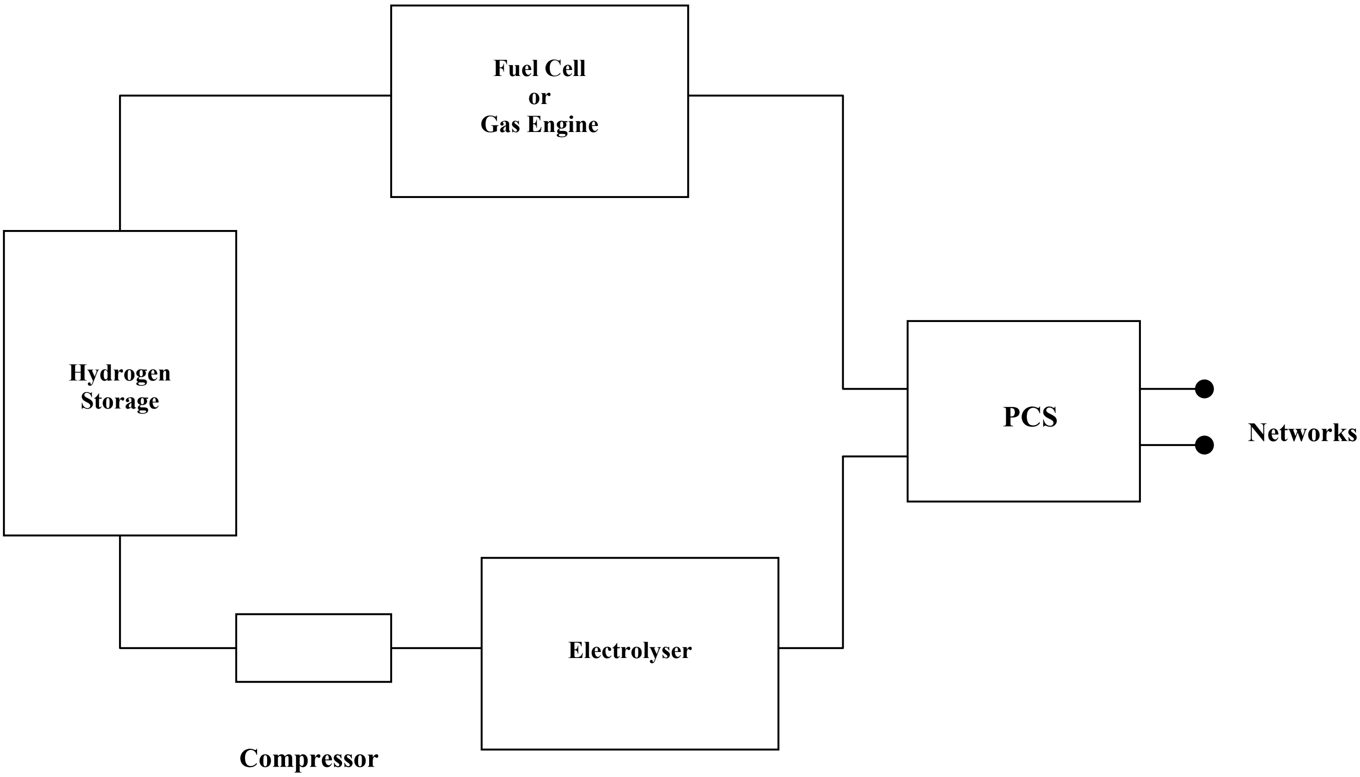

Figure 6.1 Diagrammatic Representation of Hydrogen Energy Storage System

Hydrogen based energy storage systems possess a number of inherent advantages, including:-

- the high energy density of the hydrogen itself
- the ability to implement systems over a full range of sizes, from kW scale to multi-MW capacity
- system charge rate, discharge rate and storage capacity being independent variables
- modular construction aspect, with ability to add further modules and/or re-configure systems, at later date
- potential to provide surplus hydrogen off-gas supplies for road transport applications
- environmentally benign operating characteristics

Notwithstanding these advantages, hydrogen based storage is generally somewhat at a cost disadvantage at the present time and also suffers from a relatively low round-trip efficiency (less than 50%), particularly if gas engines are used as the power generation medium. This latter aspect may however not be a totally limiting aspect, eg in a system providing significant added value to an essentially low cost input resource. Siting and licensing considerations also require careful consideration as an integral part of the overall system design, although again, these may be accommodated through proper planning and preparation.

Examples of hydrogen energy storage schemes either implemented, committed or proposed include the HARI project in Leicestershire, the PURE project in Unst, the FIRST project in Madrid and the Hunterston Hydrogen Project in Scotland. The two former examples represent small scale systems (eg up to 10 kW of generation) respectively already implemented and committed. The FIRST project represents an example of an innovative hydrogen based remote telecoms power supply solution, with the Hunterston Hydrogen Project presently being actively promoted as a large scale system (tens of MW capacity) for extracting added value from wind farm outputs, by firming up their capacity.

7 Development and Applications Potential

The previous sections have principally concentrated on a number of storage technologies and systems per se, with reference also to their applications domains. However, and notwithstanding the considerable applications benefits which may be obtained via the appropriate placement of storage within electrical power systems, there are also very considerable engineering, manufacturing and systems integration opportunities for UK industry. The present section therefore examines some of these opportunities in more detail.

A complete energy storage system comprises the following key sub-assemblies, fully integrated together to provide a complete fully functioning product :-

- the core storage technology
- a charge/discharge control system
- a power conversion system (PCS)
- associated Balance-of-Plant (B-o-P)

The make-up of the storage systems value chain, leading up to the supply of complete integrated products, is illustrated in Figure 7.1 below.

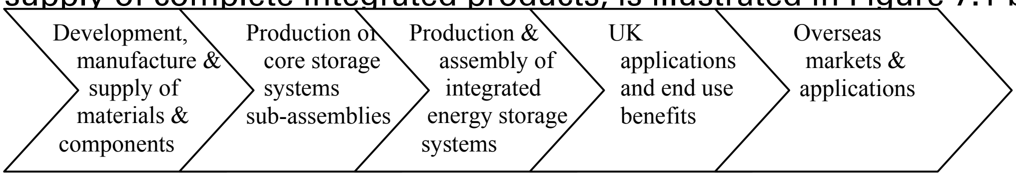

Figure 7.1 A Storage Systems value Chain

The first stage of the value chain relates to the development and manufacture of the individual sub-assemblies' constituent elements and components. These could include individual cells for battery storage, power electronics components, power systems protection and control devices and numerous other items.

The second stage in the value chain relates to the production of the complete sub-assemblies themselves, i.e. the basic "building blocks" of an integrated storage system. Examples here include the make-up of battery blocks from individual cells and the production of complete power conversion systems.

The third stage in the chain relates to the integration of these "building blocks" to form complete integrated storage systems. Such systems integration aspects can involve the sourcing of the individual sub-assemblies from within the systems integrator's organisation, from other UK suppliers or from overseas suppliers. The former option maximises the percentage of the value chain within any particular systems integrator, whereas the latter two options, although of somewhat reduced individual values, do allow greater overall flexibility in offering systems suitable for particular market needs and potentially, for accelerating overall time-to-market. There are also complementary opportunities for the supply of major sub-assemblies and components for overseas storage systems, particularly where UK industry possesses competitive advantage.

Further stages in the value chain relate to the supply and support of storage systems into the market and to the extraction of the full range of end use benefits and value streams, obtainable from the particular systems and their applications. If such applications can also help stimulate the development of an indigenous storage industry, further and additional wealth creation benefits are obtained, over and above those associated with storage related power systems benefits and carbon emissions savings. The essential key to the UK's success is in capitalising on the established strengths of the UK's power engineering and associated industries, such that they are able to compete effectively, in both the UK and overseas markets.

The development of an indigenous applications base will clearly assist UK industry in competing effectively in overseas markets. The early engagement of the power utilities and renewables sectors is likely to be an essential prerequisite to success for storage to be considered as a viable alternative to more traditional design solutions. Current regulatory initiatives, including the Innovation Funding Incentive (IFI) and the associated concept of Registered Power Zones (RPZs) will undoubtedly help to facilitate the introduction of technologies such as storage into the market. The indigenous supply of the core storage technologies themselves is not an essential pre-requisite for the supply of complete integrated storage systems by UK industry, suitable for early market entry, deployment and development. Provided appropriate commercial arrangements can be secured with the core technology suppliers, every opportunity exists for UK systems integrators to respond to the particular challenges of the UK power systems market, with its considerable overseas replication potential.

8 Conclusions

8.1 The work performed has succeeded in identifying a wide variety of energy storage technologies and systems, potentially suitable for deployment onto UK power systems networks.

8.2 A number of these technologies and systems are available on a commercial basis and are already being supplied for various overseas power utility related applications.

8.3 Notwithstanding that the majority of the current storage technology related development is taking place overseas, the make-up of integrated storage systems in themselves still provides very considerable opportunities for UK manufacturing industry and systems integrators.

8.4 The challenges of the UK market, against the backdrop of an increasing penetration of renewables and Distributed Generation resources, provides a particularly favourable environment for the introduction of new technologies, including storage.

9 Recommendations

9.1 The development of a structured strategy for the development and application of storage systems is to be recommended, both to assist in the development of the industry and in gaining the full range of applications benefits available.

9.2 The facilitation of a small series of applications demonstration schemes is to be recommended, in order to stimulate market and industry interest.

9.3 The organisation of an outbound technology mission should be considered, in order to learn from overseas best practice.