GLOBAL WATCH MISSION REPORT

Electrochemical energy storage – a mission to the USA

NOVEMBER 2004

dti

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Cover picture showing an ultracapacitor supplied by kind permission of Maxwell Technologies Inc, San Diego, CA, USA

Electrochemical energy storage

– a mission to the USA

REPORT OF A DTI GLOBAL WATCH MISSION
NOVEMBER 2004

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ACKNOWLEDGMENTS

Many organisations and individuals contributed to the success of this Global Watch Mission. The organisers and participants wish to extend particular thanks to:

- The DTI Global Watch Service
- The British Embassy in Washington, DC and the Consulate-Generals and Consulates in San Francisco, Los Angeles (covering San Diego), Houston (covering Albuquerque), Denver, Chicago (covering Detroit) and Boston
- The 32 US companies, universities, government and military organisations that generously hosted the mission team and shared their knowledge, experience and enthusiasm

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Continued overleaf

In this report, American spellings have been retained for names of US organisations, programmes, projects, etc

FOREWORD

Since 1958, International Power Sources Symposium (IPSS) has been a major world forum for debate and promotion of research and development (R&D) in the battery and fuel-cell industries: many of the foremost international scientists and technologists in this field have presented papers of significant value to fellow researchers and those from industry and military establishments looking at particular applications.

Nearly fifty years on, it has been my privilege on behalf of IPSS, with the support of the DTI's Global Watch Service, to lead and organise IPSS's first technology mission – on this occasion to the USA. The purpose of the visit was to observe and discuss developments in electrochemical energy storage (EES) and how these changes could be of benefit to the UK.

The mission brought together technologists, scientists and those with particular technology requirements, with a range of knowledge and skills, under the leadership of IPSS. The team was both experienced and well-balanced, with members drawn from industry, the military and government, supported by a senior representative of academia.

So why the USA? The mission team was aware of the considerable R&D in the whole area of electrochemistry research and advances in energy storage (ES) in North America. This has been greatly stimulated within the USA and Canada by recent power blackouts, the growing need for higher power quality, the need to find ways to integrate intermittent renewable energy (RE) sources into the power supply infrastructure, and the demand for higher efficiency, lower emission vehicles.

The mission certainly achieved its objectives and kept to its planned schedule of visits, including numerous laboratories – national and military – as well as private-sector manufacturers and research establishments.

Itinerary

Starting in California, the mission team saw at first hand the PolyPlus Battery Company's revolutionary development of a lithium battery that can be stabilised in water. Next, to the NanoGram Corporation, where laser pyrolysis of unique nanomaterials – allowing uniform powder coatings to be applied to a substrate – was fully explained.

Travelling south to visit Maxwell Technologies in San Diego, the team discussed the exciting advances being made in short-term ES using ultracapacitors. Further developments were discussed with the Electric Power Research Institute (EPRI) and at the US Department of Energy's (DOE's) Sandia National Laboratories (SNL, New Mexico) and National Renewable Energy Laboratory (NREL, Colorado).

Moving on to Michigan gave the team the opportunity to study and discuss nickel-metal hydride (Ni-MH) batteries with the senior executives of the newly created Cobasys, and then the first of four meetings in four states with research groups in the US armed services, looking especially at ways in which battery technology innovation is benefiting today's soldiers and sailors and their land transport equipment and marine vessels. Many of the advances discussed have application outside the military environment, where future collaboration will be an imperative.

Following visits to the Massachusetts Institute of Technology (MIT) in Cambridge and the DOE in Washington, DC, the final stop in our demanding itinerary was to the DOE's Energy Storage Systems Research Program Annual Peer Review meeting that enabled the mission team to gain a wide perspective of the current state of ES developments in the USA, and the challenges of integrating RE in the world's largest economy.

Lead-acid (LA) battery technology was not overlooked, with the subject of its development always showing its face. Following the mission, one of the team subsequently left for Puerto Rico, where the Puerto Rico Electric Power Authority (PREPA) has recently refurbished one of the world's largest LA ES systems.

Three other side visits were also made by team members and are written into this report, demonstrating that even more was achieved by this mission than might have been expected.

Closing remarks

No mission of this complexity can be successful without the support of many individuals: I would especially like to place on record my gratitude for the splendid help and advice that staff at the British Embassy in Washington, DC, and British Consulates across the USA were able to offer. The mission would not have been possible but for the DTI Global Watch Service and, in particular, the ever-ready help from its officers. But above all, I thank the many senior company and military executives who kindly accepted us onto their establishments and shared a common interest in the development of EES.

Finally, I hope you will find this report a useful reference point which, coupled with the feedback seminar, will be of very considerable interest and will lead to business opportunities and collaborative ventures, and stimulate ideas as to the way forward in this crucial area of electrochemistry.

R D Bailey
(Mission Leader)
Company Secretary
IPSS

EXECUTIVE SUMMARY

The context

The need to store electrical energy and convert it to electricity to meet a particular need is becoming increasingly important in society. Whether it is for *stationary* applications (such as protecting critical loads from power failures), *transport* applications (such as supplementing power in a hybrid electric vehicle), or *portable* applications (such as enabling radio communication during a combat mission), energy storage (ES) is critical. This is true in civilian life or in military activity, and research and development (R&D) is under way to provide increasingly effective technologies for ES. Indeed, in all these applications, ES is regarded as a key enabling technology.

A wide range of technologies are emerging to meet this storage need, including systems based on pumped hydro storage, compressed air energy storage, superconducting magnetic energy storage, flywheels, chemical energy storage and electrochemical energy storage (EES). Each offers different advantages and suits different applications. EES systems – batteries, ultracapacitors and flow cells – have a wide range of applications, addressing high-power to high-energy requirements in stationary, transport and portable power source markets (civil and military).

Interest in such electrochemical technologies and systems is increasing in the UK, with drivers such as integrating renewable energy sources into our energy supply, moving towards lower-carbon transport options, and the booming markets for portable consumer electronic devices helping to focus the attention of companies, universities, research organisations and government.

The USA is arguably the centre of worldwide activity in EES, and for this reason, International Power Sources Symposium (IPSS) proposed a technology mission to the USA to help to inform the UK of the emerging technologies and related opportunities.

The mission

The resulting DTI Global Watch Mission, led by IPSS, aimed to review the current status and developing trends of EES within the USA in order to identify opportunities for UK industry.

In addition to IPSS, four UK companies (QinetiQ Ltd, BT plc, Eaton Powerware Ltd and Yuasa (UK) Ltd), the Defence Science and Technology Laboratory of the UK Ministry of Defence, London South Bank University and the DTI were represented by the mission team.

Over a period of 11 days in November 2004, the team met with some 32 private and public-sector organisations across the USA (and Canada), representing a broad cross section of North American industrial, government and R&D activity in this area. A wide range of technology areas and other issues were addressed in these meetings, and the findings of the mission are presented in this report and will form the basis of a seminar to be held in Brighton in April 2005.

Key messages

The key messages from the mission are presented in full in Chapter 14 and are summarised below.

Energy storage (ES) technologies (including a number of **electrochemical technologies**) are becoming of increasing interest as an important enabling technology in stationary, transport and portable applications, both civil and military. Some transfer of technology between these markets is evident, particularly from the automotive transport sector.

Lead-acid (LA) batteries remain very competitive in terms of performance, cost and reliability, with improvements continuing to be made. They are widely used for most applications requiring power storage: integrating renewable energy sources, microgrid systems, UPS systems, etc, and look to remain so.

A wide range of **advanced battery chemistries** are the subject of R&D and demonstration in the USA, aiming to improve energy density, power density or both, at acceptable cost. While such technologies should be viewed as mid-to-long term in nature, they hold promise of doubling and even quadrupling battery energies over the next 10 to 20 years. While **lithium-ion (Li-ion)** and **nickel-metal hydride (Ni-MH)** batteries may be close to maturity, and are now finding many applications (eg in transport or military uses) where their higher initial costs are acceptable, it is technologies such as **lithium-metal-polymer (LMP)**, **lithium-iron phosphate**, **lithium-CFx**, **lithium-sulphur** and **lithium-air** batteries that hold the most promise. Companies such as Sion Power and PolyPlus Battery Company are paving the way for high energy density batteries.

Ultracapacitors are an emerging technology which appears to be on the point of becoming cheap enough for use in a very wide variety of applications and represent one of the most exciting developments in short-term ES seen during the mission. The possible use of carbon nanotubes in ultracapacitors may bring their performance close to that of a battery, although numerous practical issues remain to be addressed before they can realise their potential energy density.

The use of **flow cell (redox) batteries** to store energy in liquid electrolytes is also being demonstrated in the USA, with technology based on **vanadium-vanadium**, **zinc-bromine** and **zinc-cerium couples** either being demonstrated or under development.

The US military could become a significant 'early adopter' for advanced battery and ultracapacitor technologies.

Instability problems arising from the integration of **intermittent renewable energy (RE) sources** (eg wind energy and solar photovoltaic energy), point to the potential role of ES and **distributed generation** and the development of **'microgrids'** capable of stand-alone operation and, where appropriate, interconnection with major transmission and distribution infrastructure, as key ways to optimise such sources. ES is widely recognised as an important means of **reducing 'spinning reserve'** capacity requirements cost effectively.

Increasingly, it is the ES **system** that the users/markets are seeking, rather than the storage technology. As such, there is an increasing need for **systems integration** in the USA. The role of the network integrator and the agreement of standards in data transfer and control are becoming crucial.

A clear role is seen for **fuel cell or fuel cell hybrid systems** in stationary, portable and, particularly, transport applications, with various fuel cell technologies seen as leading technologies for different market applications.

There is scope for improving the performance of both batteries and fuel cells by using **advanced/novel-processing methods.**

Although Federal and State agency funding for the research, development and demonstration (RD&D) of EES technologies and systems is considerable compared to the UK – of the order of $105 million (~£55 million) per year – it compares unfavourably with the funding available for fuel cell and hydrogen infrastructure RD&D – of the order of $300-500 million (£160-260 million) per year: this has caused a major shift of priorities in both US industry and academia. There is a commonly held view in many of the agencies visited that not enough practical research has been completed on the role of ES technologies, particularly in more distributed energy networks relying on RE sources.

A de-skilling in electrochemical storage competencies has occurred in the USA in the last few years. This is regarded as a significant problem by the industry, particularly in light of the emerging possibilities for EES devices and systems. Other countries are 'tooling-up' to address market opportunities and attendant technology challenges.

A multitude of activities concerning EES is under way in research groups and agencies serving the US armed forces. The coordination of this activity is complex, with some overlap of activity. At the higher level, coordination is in place and linkage with other federal agencies occurs.

Several strong industry-government-academia partnerships are in place in the USA. These cost-sharing initiatives involve national laboratories and key US universities.

Opportunities exist to strengthen USA-UK linkages in collaborative RD&D. A number of opportunities have been identified during the mission (see Chapter 14).

Recommendations

The recommendations of the mission are presented in full in Chapter 14 and are summarised below. The mission team recommends that:

- Engineering companies should develop, or hold, the range of skills to provide systems integration services in the areas of ES and integration of RE sources
- Government should investigate the need for ES to overcome problems created by the increasing use of intermittent RE sources, funding research and providing incentives as appropriate
- A follow-up Global Watch Mission to North America should be considered to examine ES to enable the further integration of RE sources into the UK's electricity supply. Power quality, microgrids/distributed generation and interconnection issues should also be included
- A close watch should be kept on power source developments in the US military, and collaborations sought where possible. The US armed forces could become a significant 'early adopter' of advanced battery and ultracapacitor technologies
- There is a need for far greater transfer of technology from system development between different applications – most notably between the military and commercial sectors
- Technology and system developers in the UK should consider having their power sources assessed under various US programmes
- Clear routes for collaboration and funding between relevant US and UK organisations need to be identified and promoted

- UK universities should consider much closer links with US universities where they have a common electrochemical research objective
- There is a strong need for economic/ regulatory incentives to encourage the take-up of ES in mainstream activities
- Government, financiers and those associated with funding issues need to be made aware of developments in the EES field in order to take an innovative approach to the financing of state-of-the-art projects
- Far more concentration of effort should be placed on education of the public in general as to the need to reduce consumption. This might even mean legislation in order to reduce demand
- In those cases where UK universities have an electrochemical department, they should be encouraged by government to increase their R&D and, as appropriate, spin-off commercially-viable new business
- Government should give serious consideration to supporting the creation of a high-level, dedicated organisation to oversee this area of technology, including reviewing technological advances and facilitating collaborative ventures
- A short piece of research should be undertaken involving both UK financiers and industry specialists in the area of EES and RE to review the funding criteria adopted in the USA where innovative projects arise
- A mainstream battery magazine should be encouraged to incorporate a section on financing ES projects

1 INTRODUCTION

The need to store electrical energy and convert it to electricity to meet a particular need is becoming increasingly important in society. Whatever the application –

- stationary (for example to improve the quality of power supplied to digital equipment or to protect critical loads from power interruptions)

- transport (for example to start a heavy truck or supplement the power from an internal combustion engine in a hybrid electric vehicle)

- portable (for example to power a personal computer or camcorder or allow a soldier to maintain radio communication during a combat mission)

– energy storage (ES) is critical.

This is true in civilian life or in military activity: in both arenas, the search is on for more effective technologies for ES. Indeed, in all these applications, ES is regarded as one of the key enabling technologies, and the need for higher performance and greater cost-effectiveness of such storage devices is driving major research, development and demonstration (RD&D) activity worldwide.

The particular drivers for ES vary from application to application.

1.1 Stationary applications

ES systems are increasingly needed by power generation and transmission/distribution companies to enable load following, voltage and frequency stabilisation, management of peak loads, power quality improvement and deferral of plant upgrade investment. These activities are becoming more and more important as the reliance on uninterruptible and high-quality power grows for critical (and, increasingly, digital) loads.

Power utilities across North America, Europe and Asia are responding by installing ES and management systems that can provide ‘ride-through’ for momentary outages, and extended protection for longer outages. Coupled with advanced power electronics, ES systems can reduce harmonic distortions and eliminate voltage surges and sags.

Increasing the proportion of electricity generated from renewable energy (RE) sources such as wind, solar, waves, tidal streams and biomass is a key strategy of many countries – including the UK – as a means of reducing emissions of greenhouse gases, harnessing local energy resources, and improving local air quality. However, many of these sources are intermittent by nature, with supply not necessarily coincident with demand. In combination with RE resources, ES can increase the value of wind-generated and photovoltaic (PV) electricity, optimising the match between periods of peak customer demand and generation: this will naturally have the effect of increasing the amount of RE that a transmission grid can accommodate without suffering adversely.

RE sources are also examples of what are generally termed ‘distributed energy resources’ (DER). Such resources (which also include technologies such as microturbines and fuel cells) are creating increasing interest, as they offer the prospect of localised ‘microgrids’ which may tie-in to larger transmission grids, or may be stand-alone (or capable of either mode of operation). ES technology is a key enabling technology for both tied-in and stand-alone microgrids.

In some cases, energy is stored almost as a ‘commodity’. An example of this is the Joint European Torus (JET) nuclear fusion project at Culham in Oxfordshire, where energy is stored in a flywheel storage system for use in high-power experiments.

These stationary applications for ES have different requirements in terms of power and discharge times, as shown in Exhibit 1.1

1.2 Transport applications

The imperative need to develop more sustainable transportation, with the associated drivers of improved efficiency, reduced greenhouse gas emissions, reduced reliance on imported oil, and improved local air quality, is having a major impact on the development of all forms of transport. This is particularly evident in road vehicles (ie passenger cars, light trucks, heavy goods vehicles and buses), with lightweight/smaller engine vehicles, advanced internal combustion engine (ICE) vehicles, electric vehicles (EVs), hybrid electric/ICE vehicles (HEVs), and even hydrogen ICE (HICE) vehicles and fuel cell vehicles (FCVs) being marketed or under demonstration.

Conventional LA batteries are being replaced by more advanced LA-type batteries or advanced batteries using nickel-metal hydride

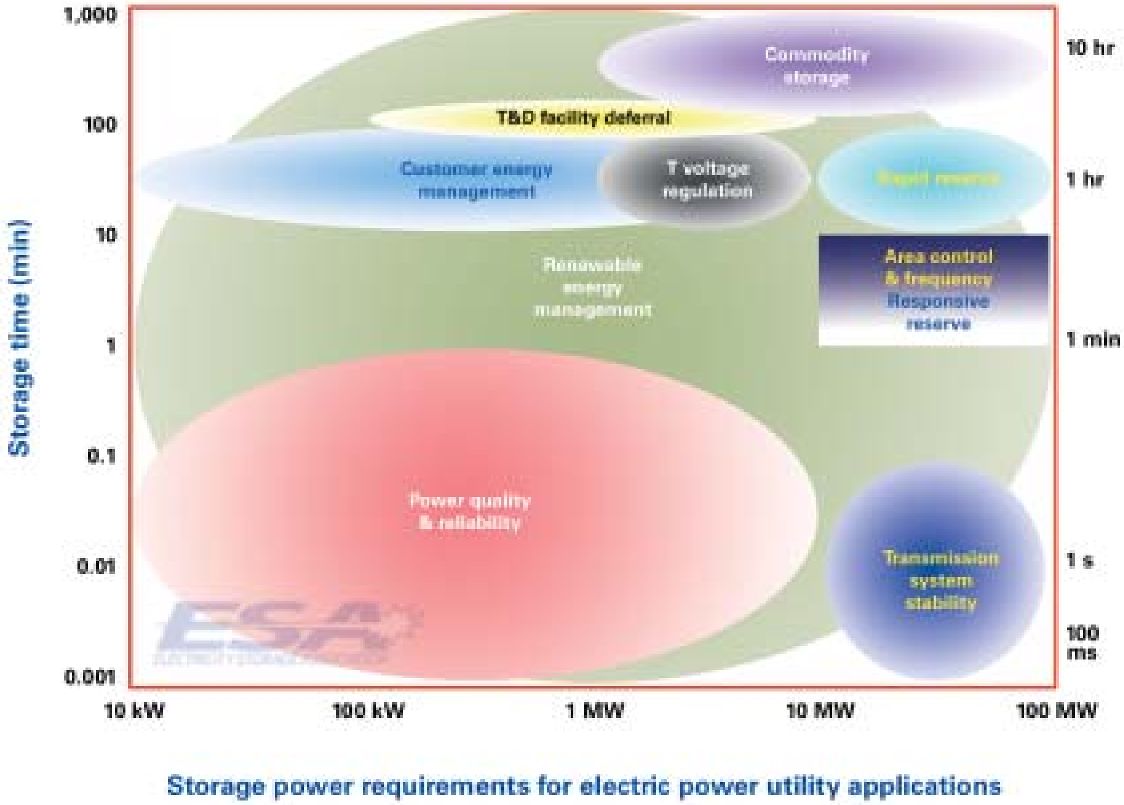

Exhibit 1.1 Stationary applications of ES (source: ESA, using data from SNL[1]*)*

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[1] Sandia National Laboratories. *Energy Storage Opportunities Analysis, Phase II Final Report: A Study for the DOE Energy Storage Systems Program.* SAND2002-1314, May 2002. www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2002/021314.pdf

(Ni-MH) or lithium chemistry, or electrochemical ultracapacitors. Size, weight, power density, energy density, cost, safety and manufacturability issues are driving international R&D activity, with different parameters being critical in different types of vehicle. In all cases, however, the need for stored energy is increasingly important – a fact not lost on battery manufacturers.

While the drivers are different, military transportation applications are also demanding more advanced battery types (or alternatives). The growing need for on-board power, 'exportable' power (eg to run ancillary military equipment) and battery charging equipment, together with specialist requirements such as ultra-ruggedness, 'silent watch' capability and low heat-signature, all present significant R&D challenges.

1.3 Portable applications

The explosive growth in portable consumer electronic devices such as personal computers (PCs), PDAs, digital cameras, camcorders, mobile phones, handheld electronic games, etc, has led to an almost insatiable demand for smaller, higher-power, longer-life and cheaper ES devices.

In military arenas, there has been a similar growth in the need for portable power sources. During World War II, the average foot-soldier had a power demand of 1-3 W – now, the average power demand of a US infantry soldier is approaching 100 W. Mission success is now, at least in part, reliant on battery life and weight.

All of these drivers are intensifying international R&D for better power sources for portable equipment.

1.4 Energy storage (ES) technologies

A wide range of technologies have evolved (and continue to evolve) for energy storage. These are summarised in Exhibit 1.2.

As has already been described, ES technologies cover a broad spectrum of applications ranging from fast, power-quality applications, to slow, energy-management applications: these applications require energy discharges from a fraction of a second in *high-power* applications to hours or tens of hours in *high-energy* applications.

The high-power end of the spectrum includes power-quality and uninterruptible power supply (UPS) applications, where ES technologies such as ultracapacitors, flywheels, SMES, etc, are used in fractions of a second to, for example, improve reliability on a transmission grid, start a vehicle or provide high power to a missile system.

The high-energy end of the spectrum includes energy-management applications, where ES technologies such as PHS, CAES, batteries, flow cells, etc, are used in daily cycles to, for example, undertake load levelling on a transmission grid, drive an EV, or power a mobile phone or military communications system.

Exhibit 1.3 illustrates the applicability of different ES technologies to these different high-power/energy situations.

Of course, it's not just the discharge time and power rating that ultimately dictate what ES system is deployed, but rather a combination of performance parameters. These parameters also include size, weight, life efficiency, capital cost and cost per cycle.

1.5 Electrochemical energy storage (EES) technologies

EES systems (ie batteries, ultracapacitors and flow cells) have a wide range of applications across the high-power/energy spectrum. As such, they are the subject of considerable R&D interest, with systems finding

Exhibit 1.2

Options for energy storage (ES)

Pumped hydro storage (PHS)

Uses two water reservoirs, separated vertically. During off-peak hours, water is pumped from the lower reservoir to the upper reservoir. When required, the water flow is reversed to generate electricity. First deployed in Italy and Switzerland in the 1890s. Over 90 GW of PHS is deployed worldwide, eg Dinorwig in the UK.

Compressed air energy storage (CAES)

Similar to PHS except that the energy is stored by pumping air into underground caverns rather than pumping water to a higher elevation. The stored energy can be recovered by combusting the compressed air with gas in a gas turbine. First deployed in Germany in 1978 (290 MW). A second plant is now operational in the USA (110 MW).

Superconducting magnetic energy storage (SMES)

Energy is stored in magnetic fields associated with a current flowing in a solenoid or torus of superconducting material mounted inside a very-low-temperature, insulated chamber cooled by liquefied gases to <100 K. SMES systems are currently only at the demonstration stage.

Flywheels

Most modern flywheel storage systems consist of a large rotating cylinder that is substantially supported on a stator by magnetically levitated bearings to eliminate bearing wear and increase system life. To maintain efficiency, the system is operated in a low-vacuum environment to reduce drag. The flywheel is connected to a motor/generator. Widely deployed.

Chemical energy storage (CES)

The conversion of electrical energy into its equivalent chemical potential offers the basis for CES. Hydrogen, generated by electrolysis and stored as either a compressed gas or refrigerated liquid, is the basis of the most common CES approach, with conversion to electricity by a fuel cell. Reversible fuel cells are also under development.

Electrochemical energy storage (EES)

Use of devices that can store electrical energy in the form of chemical energy for transformation back to electrical energy when needed. Conventional lead-acid (LA) and nickel-cadmium (Ni-Cd) batteries harness this principle, as do advanced batteries, electrochemical ultracapacitors, and flow cells (containing a circulating electrolyte).

burgeoning deployment in stationary, transport and portable applications – both civil and military.

An overview of the range of EES technologies is presented in Exhibit 1.4.

The worldwide market for EES is in excess of $43 billion (£23 billion) annually and is growing at a compound annual rate of 7%. In the UK, too, interest is rising in EES technologies for a range of applications.

This interest is reflected within the Board of International Power Sources Symposium (IPSS), and led to a proposal to the DTI Global Watch Service for a technology mission to take place in November 2004.

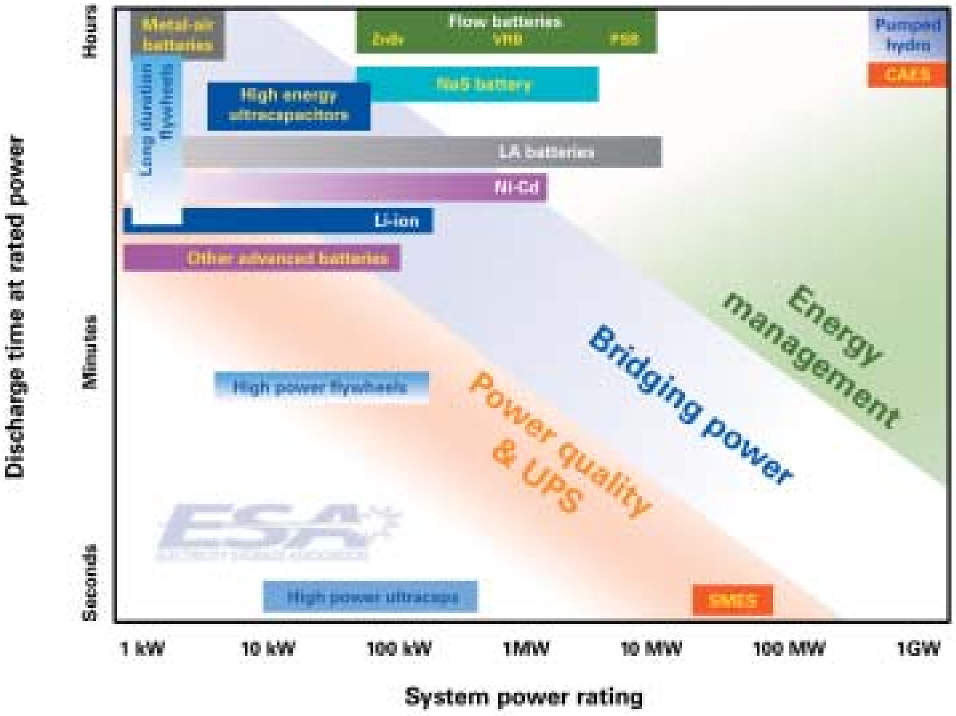

Exhibit 1.3 Applicability of ES systems to high-power/energy situations (source: ESA)

Exhibit 1.4

Electrochemical energy storage (EES) technologies

Batteries

- Lead-acid (LA), valve-regulated LA (VRLA), gelled LA, spiral-wound LA, bipolar LA (BLA)
- Nickel-cadmium (Ni-Cd)
- Nickel-metal hydride (Ni-MH)
- Li-ion (high energy), Li-ion (high power)
- Li-ion-polymer (LIP)
- Li-iron phosphate (‘Saphion’), Saphion-polymer
- Li-sulphur (Li-S)
- Li-metal-polymer (LMP)
- Li-air
- Li-water
- Li-iron disulphide
- Sodium-sulphur (Na-S)
- Sodium-metal chloride (‘Zebra’)

Electrochemical capacitors

- Double-layer capacitors (‘supercapacitors’/’ultracapacitors’)

Flow cells

- Zinc bromide ($ZnBr_2$)
- Sodium sulphide/bromide (NaS/NaBr)
- Vanadium redox

The USA is, without doubt, the centre of worldwide activity on EES, with a wide range of basic research, applied research, industrial development, demonstration and deployment, covering just about every relevant battery chemistry, ultracapacitors, and flow cells. This comprehensive RD&D activity involves a wide range of industry, academia and government (federal and state level), and addresses the full range of stationary, transport and portable applications, both civil and military.

With this in mind, IPSS proposed that the logical focus for the proposed Global Watch Mission was the USA.

2 MISSION OVERVIEW

This Global Watch Mission was supported by the DTI Global Watch Service, which backs short fact-finding visits overseas by small groups of technical experts from UK companies and leading academic institutes, to identify and learn from the best practice and technological developments in leading companies and research organisations overseas. DTI funds the travel costs and helps towards the coordinating body's costs of organising and promoting the mission. Full details of Global Watch Missions and other activities of the DTI Global Watch Service can be found at www.globalwatchonline.com.

2.1 Aims and objectives

The mission's overall aim was to review the current status and developing trends of EES within the USA in order to identify opportunities for UK industry in this area of technology. Through gaining a better understanding of EES technology in the USA, the mission aimed to help UK industry by stimulating an improved awareness of products and associated developments, encouraging collaboration and technology transfer, and bringing relevant UK technology to the notice of US organisations with the aim of promoting exports of UK systems, devices and intellectual property (IP).

Underlying this high-level aim were a number of specific objectives, namely to:

- Review the current status of EES technology across a range of US companies and government bodies
- Support the development of UK manufacturers and users through dissemination of the mission findings
- Strengthen and reinforce existing relationships and create new value relationships for UK industry
- Introduce UK organisations to leading-edge technology, and heighten awareness of potential development opportunities
- Encourage closer working relationships

2.2 Participants

The mission was organised by International Power Sources Symposium (IPSS) and led by Mr Bob Bailey, Company Secretary of IPSS.

IPSS has the overall aim of advancing the education of the general public by improving understanding and knowledge in the field of R&D in the use of non-mechanical power sources, particularly electrochemical devices such as batteries and fuel cells, as well as PV and other non-electrochemical power sources.

Formed in 1958, IPSS is run by a board of trustees drawn from UK government departments, academia, battery and fuel cell manufacturers, supply companies and users. The main functions of IPSS are to hold major symposia every two years, together with regular educational seminars.

The organisation is a private non-profit company, limited by guarantee and is a registered charity.

The biennial symposia provide an open forum for the presentation and discussion of current thinking on R&D into the use of non-mechanical power sources, EES systems, and potential applications. Such sources include primary, secondary and reserve batteries, fuel cells, PV and thermoelectric systems. In achieving its aims, IPSS encourages the use of environmentally friendly non-mechanical power sources. With each symposium, papers are called for on a worldwide basis, selected and presented. These papers form the basis of an authoritative book (now CD-ROM format) that is seen as a standard work and sold around the world.[2]

Several IPSS trustees have been involved in previous DTI Global Watch Missions.

Four UK companies – **QinetiQ Ltd**, **BT plc**, **Eaton Powerware Ltd** and **Yuasa (UK) Ltd** – were represented on the mission, covering a broad range of technical interests in EES and direct current (DC) power in a range of applications (stationary, transport and portable applications both in the civil and military markets).

Coordinating body and supporting organisations	
International Power Sources Symposium (IPSS)	Mr Bob Bailey
DTI International Technology Promoters (ITP) network	Mr Philip Sharman
Industrial participants	
QinetiQ Ltd	Dr Emmanuel Eweka
BT plc	Mr Mark Kniveton
Eaton Powerware Ltd	Mr Mick Morling
Yuasa (UK) Ltd	Mr Peter Stevenson
Research organisations and academia	
Defence Science and Technology Laboratory (DSTL)	Dr Darren Browning
London South Bank University (LSBU)	Professor John Turner Mrs Sharon Holmes

Exhibit 2.1 Mission team list

Exhibit 2.2 Mission team at NREL (Golden, CO). L to R: Darren Browning, Mark Kniveton, Peter Stevenson, Emmanuel Eweka, Philip Sharman, Sharon Holmes, Mick Morling, John Turner, Bob Bailey

In addition, military technology interests were represented by the **Defence Science and Technology Laboratory (DSTL)** of the UK Ministry of Defence (MOD).

UK academia and the scientific community were represented by **London South Bank University (LSBU)**.

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[2] The latest publication is: *Power Sources 19: Proceedings of the 23rd International Power Sources Symposium, Amsterdam, The Netherlands, 22-24 September 2003*. Austin Attewell (Ed). For details, see www.ipss.org.uk/ps19.shtml

IPSS has extensive contacts with organisations currently concerned with EES technologies, issues and opportunities in the UK. To support IPSS in this role, and to bring additional US contacts to bear, the mission team included the DTI International Technology Promoter (ITP) for sustainable energy and environmental technologies for North America.

The mission team members and their respective affiliations are summarised in Exhibit 2.1, with full particulars and contact details included in Appendix A.

2.3 Visits

The mission formally took place during 1-10 November 2004, although some members undertook additional meetings on 29 October and 11-12 November. Since the key outputs and lessons learnt from these additional meetings have been shared with the team and are pertinent to the mission, these additional meetings are included within the report and are regarded as an integral part of the mission.

In total, the group (or individuals in it) met with some 32 private and public-sector bodies across the USA (and Canada and Puerto Rico). The mission also coincided with the US Department of Energy's (DOE's) Annual Peer Review meeting for its Energy Storage Systems Research Program in Washington, DC, and a number of mission members attended the second day of this meeting. The itinerary for the mission is shown in Exhibit 2.3. Contact details for the organisations visited are included in Appendix B.

Date (2004)	Location	Visit/meeting
29 October	Tucson, AZ* Montreal, QC, Canada**	Sion Power Corp Avestor
1 November	San Francisco Bay Area, CA	NanoGram Corp Electric Power Research Institute (EPRI) Electricity Storage Association (ESA) California Energy Commission (CEC) Advanced Energy Analysis (AEA) Longitude 122 West Inc Symons/EECI Electrochemical Design Associates (EDA) PolyPlus Battery Co Electrochemical Society – San Francisco Section
2 November	San Diego, CA	Maxwell Technologies Inc
3 November	Albuquerque, NM	Sandia National Laboratories (SNL)
4 November	Golden, CO	National Renewable Energy Laboratory (NREL)
5 November	Warren, MI Troy, MI	US Army RDECOM – TACOM US Army RDECOM – TARDEC US Army National Automotive Center (NAC) Cobasys
8 November	Cambridge, MA	Massachusetts Institute of Technology (MIT) Institute for Soldier Nanotechnologies (ISN)
9 November	Fort Monmouth, Red Bank, NJ	US Army RDECOM – CECOM US Army RDECOM – CERDEC US Army Power Sources Center of Excellence
10 November	West Bethesda, MD Washington, DC	US Navy NAVSEA – NSWC Carderock Division US Department of Energy (DOE) – EERE Defense Sciences Office (DSO) – DARPA Advanced Lead-Acid Battery Consortium (ALABC)
11 November	Washington, DC*** Raleigh, NC****	US DOE – OETD: ES Systems Annual Peer Review Eaton Powerware Inc
12 November	Adelphi, MD* San Juan, PR*****	US Army Research Laboratory (ARL) Puerto Rico Electric Power Authority (PREPA)

Exhibit 2.3 Mission itinerary

* Darren Browning and Emmanuel Eweka only; ** Mark Kniveton only; *** Mission team with exception of Mark Kniveton and Mick Morling;

**** Mark Kniveton and Mick Morling only; ***** Peter Stevenson only

Exhibit 2.4 Mission route

2.4 Technology areas and other issues

The mission addressed both technical and non-technical issues associated with EES. In terms of technical issues, it covered the broad range of electrochemistries associated with conventional and advanced batteries and hybrid batteries, and double-layer capacitors/supercapacitors (known as ‘ultracapacitors’ in the USA) that are being researched, developed and deployed in the USA, and the experiences gained to date. In terms of non-technical issues, the mission explored associated economic and environmental aspects, as well as applications and marketing issues.

2.5 Questions addressed

The mission team identified a list of questions that it sought to address on the visits. These questions, categorised under the broad areas listed in Section 2.4, were circulated to the organisations to be visited prior to the mission commencing.

The mission questions are included as Appendix C to this report.

2.6 Mission seminar

A one-day seminar will be held on 18 April 2005 in conjunction with the IPSS Symposium in Brighton to disseminate the findings of the mission to a wide group of stakeholders and interested parties. The event is expected to attract participants from key parts of UK industry, academia and government with interests in EES.

3 LEAD-ACID (LA) BATTERY TECHNOLOGIES

Lead-acid (LA) batteries are one of the oldest forms of EES device. Despite the emergence of many competing storage technologies during its 150-year history, LA retains the dominant position with a world market of ~$10 billion (~£5.3 billion) per annum. It has not been displaced from any of the traditional applications in which it is entrenched, such as automotive, traction and stationary storage, and is generally used as the benchmark against which new battery systems are quoted.

In many cases the technical specifications of alternative batteries are superior, but the current cost range of 2-5 p/Wh is an order of magnitude cheaper than some of these alternatives. For this reason it is still true that if LA can be used then it will be used for a particular application. Even where the superior longevity of an alternative system indicates that whole-life costs may be lower, there are many instances where the initial cheapness and ready availability of LA proves decisive in the user's choice.

Another reason for the continued success of LA technology has been the efforts of manufacturers to adapt the architecture of cells to optimise the performance features that are important for particular applications. This process has generally involved compromising other desirable features so that no single design has come to dominate the entire range of applications. The result is that there is today a wide array of products available for systems integrators to choose from, and it is not always clear which is the most suitable for a new or modified purpose.

From discussions and reports received during this mission it is clear that the ingenuity of battery designers and systems engineers is far from discharged with respect to continuing enhancement of LA technology. Even the proponents of some alternative storage cells were able to identify complementary features of LA cells that could result in the feasibility of new applications, which neither technology alone could satisfy.

3.1 LA technology

3.1.1 Basic chemistry

The first practical LA battery was developed by Gaston Planté in 1859. The fundamental electrochemical processes involved in EES have not changed since, although the manufacturing process has evolved in several respects.

The positive electrode active material is composed of lead dioxide (PbO_2) and the negative of metallic lead (Pb). Both are in a highly porous form to provide a high surface for the interaction with the third active material – sulphuric acid (H_2SO_4). The product of the discharge reaction in both cases is lead sulphate ($PbSO_4$).

The half-cell reactions are as follows:

Positive: $PbO_2 + 3H^+ + HSO_4^- + 2e^- \underset{\xrightarrow{\text{Discharge}}}{\xleftarrow{\text{Charge}}} PbSO_4 + 2H_2O$

Negative: $Pb + HSO_4^- \underset{\xrightarrow{\text{Discharge}}}{\xleftarrow{\text{Charge}}} PbSO_4 + H^+ + 2e^-$

The overall reaction is:

$$PbO_2 + Pb + 2H_2SO_4 \underset{\xrightarrow{\text{Discharge}}}{\xleftarrow{\text{Charge}}} 2PbSO_4 + 2H_2O$$

The theoretical energy available from the discharge reaction is ~150 Wh/kg (55 kJ/kg) of active materials, although in commercial cells values in the range 30-40 Wh/kg are typically achieved.

The sulphuric acid also acts as an ionic electrolyte for the cell, and is present as an aqueous solution. It is not possible to fully recharge the electrode plates, particularly the positives, without bringing their potential to a level that also causes electrolysis of the water present in this solution. The processes at the two electrodes are:

Positive: $2H_2O \longrightarrow O_2 + 4H^+ + 4e^-$

Negative: $4H^+ + 4e^- \longrightarrow 2H_2$

The net effect is the conversion of water into hydrogen and oxygen gases, which may escape from the cell. The consequence is that cells will dry out and cease to function unless steps are taken either to replace the water or to modify the electrolysis process. Both strategies are employed, and are differentiated by the disposition of the electrolyte within the cell.

3.1.2 Flooded and absorbed electrolyte systems

Traditional LA battery designs consist of arrays of positive and negative plates that are completely submerged in diluted sulphuric acid solution. Electrolysis occurs as described above but the rate of gas production is highly dependent on the types of lead alloy that are employed in the construction of the plates and internal connectors. Where antimony is used as an alloying agent, to yield mechanically robust plates with good deep-cycling characteristics, water must be added at intervals to prevent loss of capacity. The rate of water loss can be significantly reduced by employing electrode structures made of pure lead or alloys containing calcium and/or tin. In applications such as automotive starting, lighting and ignition (SLI), where batteries are not subjected to continuous charging, it has been possible to include sufficient excess water during manufacture to eliminate the requirement for topping-up during the life of the battery.

Another technique employed in these flooded electrolyte designs, to extend periods between maintenance, is the inclusion of catalyst plugs that promote the recombination of hydrogen and oxygen within the cell. The high cost and susceptibility of these devices to poisoning led to the development of an alternative method for gas recombination within the cell.

The finely divided ‘sponge’ lead active mass of the negative plate is extremely reactive towards oxygen molecules. If transport of the oxygen produced at the positive plate can be facilitated sufficiently, it is possible to recombine all the oxygen generated within the cell. At the same time, the reaction with oxygen pins the potential of the negative plate at a level where hydrogen production is largely eliminated also. The keys to this technology were developed in the 1960s and early 1970s. They involve methods to immobilise the liquid sulphuric acid electrolyte between the electrode plates, leaving microscopic gas channels through which oxygen can pass rapidly from positive to negative plates. Both of the techniques employ the use of silicates as the absorbing agents, either as a colloidal gel or within the pores of glass microfibre mats.

Because of the accessibility of the negative active mass to oxygen, it is necessary to prevent the ingress of atmospheric oxygen, which would rapidly discharge the negative plates. For this reason, oxygen recombining cells were initially termed 'sealed' LA batteries to distinguish them from traditional vented LA (VLA) cells. This was a misnomer because most cells are not fully sealed and are designed to release gases, in the event of an internal pressure rise, via a resealable valve. To clarify this effect, oxygen recombination types are more correctly termed valve-regulated LA (VRLA) cells.

3.1.3 LA battery architectures

Planté cells

Although nearly 150 years old, this design is still in small-scale production and illustrates the conservatism of some fields of battery application, especially where safety and reliability are critical. The positive plate is manufactured from a solid lead casting, upon which the positive active material is formed by repeated charging and discharging in a sulphuric acid solution. The energy density is very low, and regular maintenance is required, but extremely long life is normal for such systems – extending to 30-40 years. Discharges are infrequent, but usually safety-critical functions are powered in utility substations and power-generation plants.

Flat-plate (Faure) cells

Flat-plate LA cells have been the most common design for the past 100 years. The active material precursor is prepared as a paste of leady oxides mixed with water, sulphuric acid and other additives and then applied to a flat grid structure. The electrode panel is conditioned to produce a porous structure which is finally converted to the charged condition electrochemically. The grid structure which supports the active material has traditionally been cast from molten lead alloys, but is now increasingly produced by slitting, punching or expanding coils of lead alloy strip. This is the dominant architecture for SLI and VRLA batteries.

A cell usually consists of a stack of alternating positive and negative plates separated by insulating sheets. The plates of each polarity are joined in parallel at the top of the cell. See Exhibit 3.1.

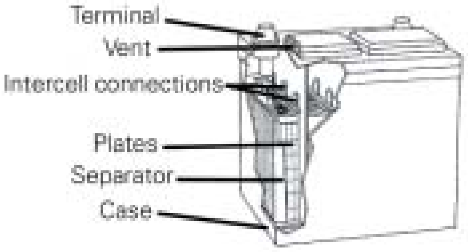

Exhibit 3.1 LA battery: flat-plate (Faure) cells

Tubular-plate cells

The positive grid in this architecture is cast in a comb-like structure. The tines of the comb are enveloped in a woven fabric tube, and the space between tine and tube packed with active precursor paste or granules. The negative plates are normally produced in flat-plate configuration. This architecture is most commonly applied in vented systems, but gel-type VRLA products are available. The high compression applied to the positive active material gives this design advantages in deep-cycling applications, but its high-rate performance is relatively poor. See Exhibit 3.2.

Exhibit 3.2 LA battery: tubular-plate cells (source: PREPA)

Spiral-wound cells

Spiral-wound active material precursors are pasted onto lead strip or punched grid. Positive and negative strips are superimposed with an insulating separator between. This composite strip is wound into a ‘swiss roll’ configuration and inserted into a cylindrical plastic container. This configuration provides very high surface-area electrodes with tight compression of the components. This results in cells with high power densities – comparable to capacitors, but with higher ES capabilities.

This design has been identified for development in hybrid electric vehicle (HEV) applications as part of a programme coordinated by the International Lead Zinc Research Organisation (ILZRO) based in North Carolina. This project aims to re-establish LA technology as a viable alternative to the Ni-MH cells that are currently used in commercial HEV products from Toyota and Honda, and from the main US automobile manufacturers as they join this rapidly growing market. An illustration of an individual 2 V cell and complete battery module is shown in Exhibit 3.3.

Exhibit 3.3 LA battery: spiral-wound cells – (a) individual 2 V cell; (b) complete battery module (source: ALABC/Enersys)

During preceding studies, many of the difficulties associated with vehicle applications – such as deep discharging over many hundreds of cycles – have been overcome. The HEV battery must be able to withstand the unique requirement for accepting rapid discharging and recharging over many cycles without reaching a full state of charge. This regime leads to rapid degradation of the negative plates in conventional designs due to an accumulation of lead sulphate within the negative active material. Intensive study in this area, as reported at the DOE Energy Storage Systems Research Program Annual Peer Review meeting, has identified that the addition of carbon to the negative electrode yields a significant improvement to battery life.

It is common practice in many LA products to add ~0.2% (by weight) of carbon to the negative active material. To achieve improvements in partial state of charge (PSoC) conditions, it is necessary to add at least 2% of carbon. This area of research is currently one of the most active in the LA industry, both to identify the mechanism of the electrochemical effects and to find the most effective carbon materials.

Another presentation at the DOE Peer Review meeting highlighted an area of convergence between two technologies that are often viewed as competitors: LA and ultracapacitors. A limiting feature of ultracapacitors is their low ES ability. This generally restricts them to applications where high power is required for periods of seconds or a few minutes. This limitation is being addressed by the study of asymmetric ultracapacitors that combine a purely capacitive negative electrode made from carbon with an electrochemical positive electrode.

One candidate for this positive electrode is lead dioxide in a sulphuric acid electrolyte. Experiments with this type of cell have shown an increase of 3 – 4 times in the energy density compared to symmetric ultracapacitors. These cells are not commercially available, and at present are constructed in a flat-plate configuration, rather than spiral-wound, but there are interesting potential benefits for high-rate, medium-energy applications such as HEV and power conditioning.

Round cells

This unique architecture was initially developed by AT&T Bell Laboratories for long life in telecommunications applications. Cast disc-shape lead grids are used for positive and negative plates. The concentric disposition of grid wires is particularly resilient to active material displacement caused by corrosion-induced grid growth. The positive and negative plates are stacked horizontally in cylindrical containers covered with electrolyte.

The high cost and relatively low-rate performance has limited this design to telecommunications applications only, but the life achieved for the product is typically much longer than the 20 years expected at the design phase.

Bipolar LA (BLA) batteries

This concept is particularly suited to the construction of high-voltage mono-blocs because it is based on a simple, sandwich architecture. The positive and negative active materials are applied to each side of electronically conducting plates. By stacking these plates, interspersed with suitable insulating separators, a high-voltage battery can be produced (see Exhibit 3.4).

Other advantages of this design are the elimination of the lead-alloy grids, top connectors and posts, which are passive components that can make up to 50% of the lead content of the battery. This helps to increase the energy density to up to double that of conventional designs – potentially bringing it to the same level as Ni-Cd or Ni-MH technology. The current is transmitted across a much larger surface area and shorter path-lengths between cells that can reduce internal resistance greatly.

One of the earliest applications of this technology was for the study of the physics of large magnetic fields by Kapitza in the 1920s. Power levels of 10 kW/m^2 were

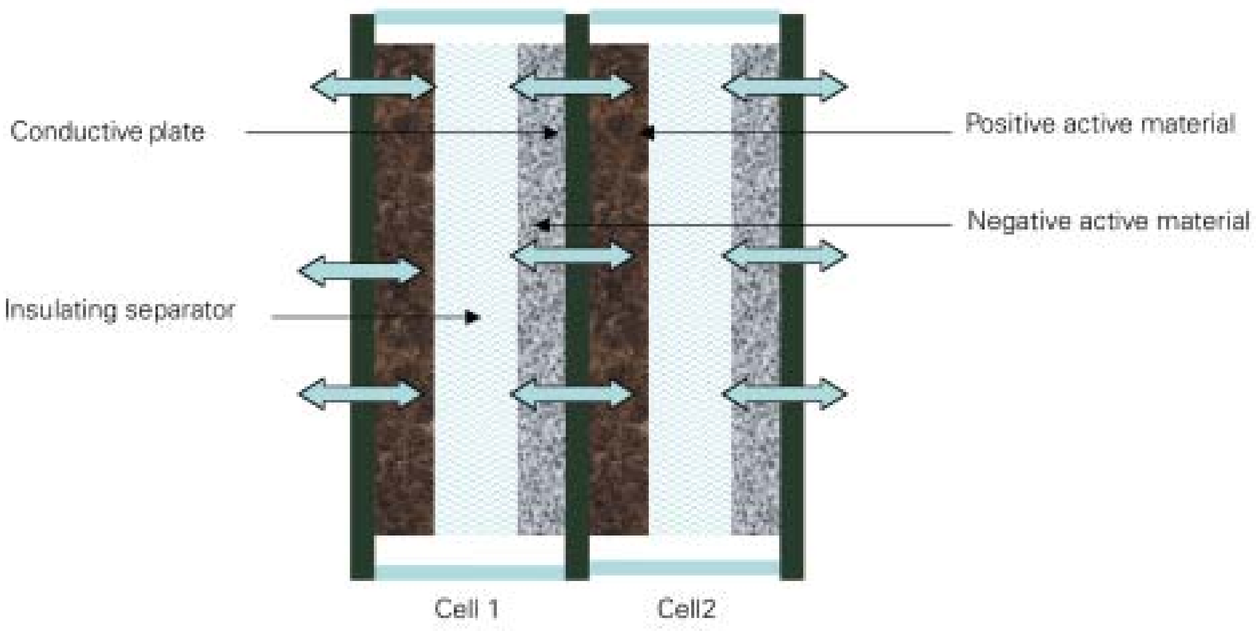

Exhibit 3.4 LA battery: bipolar LA (BLA)

achieved, but the stability of the cells made them impractical for commercial applications.

The key to this technology remains the development of an electronically conducting material that has the chemical and mechanical stability necessary to operate for many years in the presence of sulphuric acid at highly oxidising or reducing potentials. It must also be capable of maintaining electrical conductivity at the interface with positive active material, which has proven problematic even with certain lead-alloy grid substrates. Current examples of the activity in this area include companies in Europe and America:

- **F-Power** (Sweden) and independently **Cat Solar** (USA) – carbon foam/felt porous matrix filled with lead deposits to produce a conductive non-porous plate
- **TNO** (Netherlands) – carbon particles bonded within a polymer film
- **Atraverda** (UK) – conductive titanium oxide particles forming a composite within an epoxy resin matrix

Electrochemical Design Associates Inc (EDA) of Berkeley, CA, has been developing this technology with the intention of applying it to HEVs. No details were provided of the electrode composition, due to pending patent applications. Key performance parameters compared with other battery types are provided in Exhibit 3.5.

At present, Toyota is leading the market in terms of volumes of HEVs sold, especially in the California area, where state regulations are driving this activity. The Ni-MH battery used in this application currently costs $6,000 (~£3,150), and much of this is not recovered in the selling price of each vehicle. EDA is currently working with Lotus Engineering in the UK to produce an equivalent product with projected costs closer to $600 (~£315) per battery.

	Average energy density (Wh/kg)	Peak power density HEVs duty (W/kg)	Relative cost ($/kWh)
Conventional LA traction	35	110	150
Pseudo BLA (Horizon/Beijing Powertronics Battery Co)	40	231	150
Ni-MH	70	200	250-600
True BLA (Atraverda)	80	660	>>EDA
True BLA (EDA)	80	700-800*	<<150
Li-ion (Valence Technology)	96	~900	2,544
Li-metal (Avestor)	100	~1,500	>>2,000

Exhibit 3.5 Performance of BLA batteries compared with other types (source: EDA)

** Estimated*

4 LITHIUM-ION BATTERY TECHNOLOGIES

The exponential growth in portable electronic devices such as mobile phones, digital cameras, camcorders and laptop/notebook PCs in the last ten years has generated an increased interest in compact, lightweight batteries offering high energy densities. In addition, growing global environmental concerns are driving the development of advanced batteries for EV and HEV applications.

Lithium-ion (Li-ion) batteries are appealing for these applications as they provide the highest energy density compared with the other battery systems such as LA, Ni-Cd and Ni-MH (see Exhibit 4.1).

The market for rechargeable Li-ion batteries (including Li-ion-polymer (LIP) batteries) has exhibited very high growth over the past ten years and is now estimated to be ~\$4.5 billion (~£2.4 billion) per annum and continuing to grow strongly. The primary driver for this remarkable growth has been the so-called ‘cordless society’, ie where users demand complete freedom from

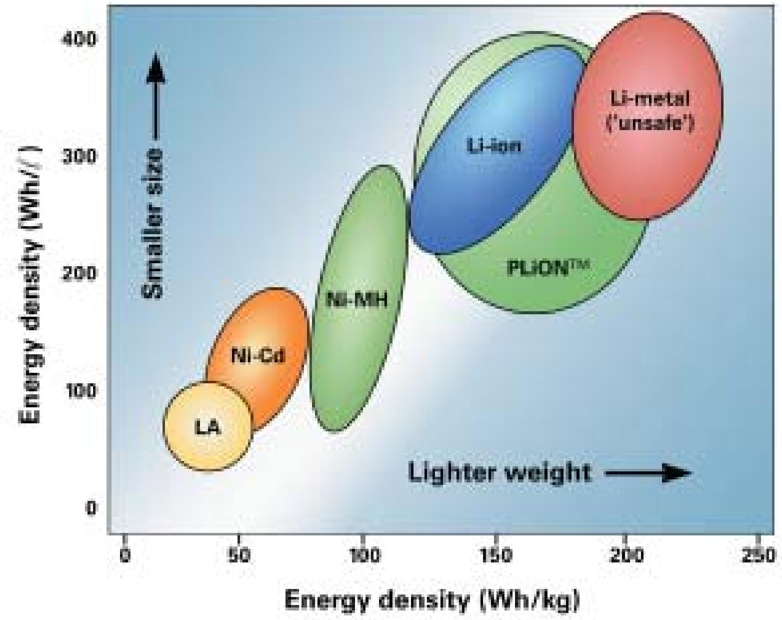

Exhibit 4.1 Energy characteristics of different battery technologies

	Ni-Cd	Ni-MH	LA	Li-ion	Li-ion polymer
Gravimetric energy density (Wh/kg)	45-80	60-120	30-50	110-160	100-130
Internal resistance – includes peripheral circuits (mW)	100-200 (6 V pack)	200-300 (6 V pack)	<100 (12 V pack)	150-250 (7.2 V pack)	200-300 (7.2 V pack)
Cycle life – to 80% of initial capacity (cycles)	1,500	300-500	200-300	500-1,000	300-500
Fast charge time (h)	1 (typical)	2-4	8-16	2-4	2-4
Overcharge tolerance	moderate	low	high	very low	low
Self-discharge/month – at room temperature (%)	20	30	5	10	~10
Cell voltage – nominal (V)	1.25	1.25	2	3.6	3.6
Load current (C) – peak – best result	 20 1	 5 ≤0.5	 5 0.2	 >2 ≤1	 >2 ≤1
Operating temperature – discharge only (ºC)	-40 – +60	-20 –+60	-20 –+60	-20 –+60	0 – +60
Maintenance requirement	30-60 days	60-90 days	3-6 months	not required	not required
Typical battery cost ($)	50 (7.2 V)	60 (7.2 V)	25 (6 V)	100 (7.2 V)	100 (7.2 V)
Cost per cycle ($)	0.04	0.12	0.10	0.14	0.29
Commercial use since	1950	1990	1970	1991	1999

Exhibit 4.2 Characteristics of different battery technologies

mains-based electricity. Although application of Li-ion battery technology has predominantly been in portable devices (eg mobile phones, PCs, camcorders, etc), the benefits of Li-ion are such that it is likely to become the dominant battery technology of the 21st Century, finding increasing application in the transport sector (eg HEVs) and other sectors. These issues are discussed in more detail in Chapters 7 to 11.

Some of the characteristics of Li-ion systems compared with other battery systems are given in Exhibit 4.2.

The higher volumetric and gravimetric energy densities of the Li-ion cells are due to a combination of high-voltage electrochemical couples (~4 V) and non-aqueous organic electrolytes with a high electrochemical stability window which also increases the temperature range of operation. Since the initial announcement by Sony in the early 1990s, Li-ion cells have become a commercial reality because of an intense worldwide research activity on lithium insertion compounds (electrode materials), and Li-ion batteries are currently in large-scale commercial production for use in portable consumer electronics.

4.1 Li-ion technology

4.1.1 Basic chemistry

Compared with some aqueous systems, the electrochemistry should, in theory, be refreshingly simple: the electrolyte takes no part in the reaction except for conveying the electroactive lithium ions during discharge from a high-energy state in the negative electrode to a low-energy state in the positive electrode, while the electrons pass through the external circuit with a release of energy

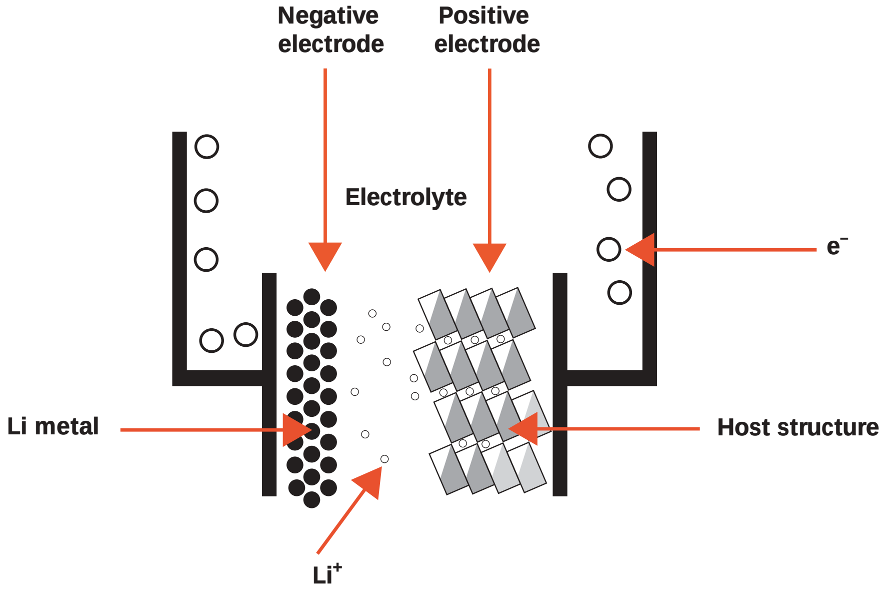

Exhibit 4.3 Charge/discharge process in Li/TiS_2

(Exhibit 4.3). The opposite reaction occurs on charge, so that rechargeability depends on the reversibility of the reactions at the electrodes.

At the positive electrode, reversibility is a consequence of the use of an insertion electrode material (host)[3], which is a solid capable of incorporating the electro-active lithium ions into a solid solution with a wide stoichiometry range. An example of such insertion materials is titanium disulphide (TiS_2), which has a layered structure and the reversible electrode reaction given in equation (1):

$$\delta Li^+ + \delta e^- + Li_xTiS_2 \rightleftharpoons Li_{x+\delta}TiS_2 \qquad (1)$$

The electrode undergoes a reversible topotactic redox reaction, meaning that it acts as a host structure which accommodates guest ions and electrons without destruction of the lattice. During discharge, lithium ions are inserted into the van der Waals gap between the sulphide layers, and the charge balance achieved by a subsequent reduction of Ti^{4+} to Ti^{3+}. On charging, the reverse process occurs, with the lithium ions being extracted and Ti^{3+} oxidised to Ti^{4+}.

The open-circuit voltage V_{oc} of such lithium cells is given by the difference between the chemical potentials of lithium in the cathode – $\mu_{Li(c)}$ – and the anode – $\mu_{Li(a)}$ – according to:

$$V_{oc} = \mu_{Li(c)} - \mu_{Li(a)} / F \qquad (2)$$

where F is the Faraday constant.

The cell voltage, V_{oc}, is determined by the energy involved in both the electron and lithium ion transfer. While the energy involved in electron transfer is related to the work functions of the cathode and the anode, the energy for Li^+ transfer is determined by the crystal structure and the coordination geometry of the site into/from which Li^+ ions are inserted/extracted. Thermodynamic stability considerations require the redox energies of the cathode (E_c) and anode (E_a) to lie within the band gap (E_g) of the electrolyte so that no unwanted reduction or oxidation (electrolyte decomposition) of the electrolyte occurs during the charge/discharge process. This electrochemical stability requirement imposes a limitation on the cell voltage as:

$$eV_{oc} = \mu_{Li(c)} - \mu_{Li(a)} < E_g \qquad (3)$$

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[3] S Yoda, extended abstract, 8th International Meeting on Lithium Batteries, Nagoya, Japan, June 1996

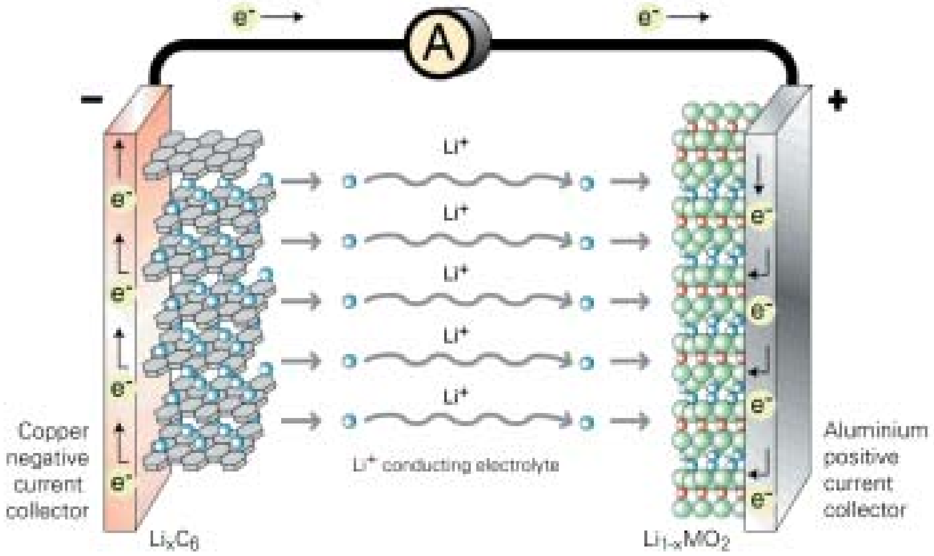

Exhibit 4.4 Li-ion battery reaction

4.1.2 Cells with insertion anodes and cathodes (‘rocking-chair’ configuration)

Despite the development of several lithium insertion compounds during the 1970s and 1980s, the commercialisation of rechargeable lithium batteries was hindered for many years until the announcement by Sony in the early 1990s. This delay was mainly due to safety and performance issues related to the use of metallic lithium as anode.[4]

The difficulties associated with metallic lithium prompted the development of the next generation of Li-ion cells based on insertion anodes and cathodes. These cells are known as ‘rocking–chair’ cells, since the Li^+ shuttles (or rocks) between the cathode and anode hosts during the charge/discharge process. The principle of operation of such a cell is shown schematically in Exhibit 4.4, and the cell reaction is given in equation (4).

$$LiCoO_2 \rightleftharpoons xLi^+ + xe^- + Li_{1-x}CoO_2 \qquad (4)$$

Here the negative electrode is also composed of an insertion electrode, with advantages of dimensional and improved chemical stability. No lithium metal need exist in the cell – the lithium is always held as a guest in one of the electrodes depending on the state of charge. However, the specific charge is decreased due to the excess weight of the anode and, bearing this in mind, a careful selection of cathode and anode pairs is required in order to achieve an acceptable cell voltage of at least 3 V and to realise a reasonable energy.

Transition metal oxides such as $LiCoO_2$, $LiNiO_2$ and $LiMn_2O_4$, having a high potential of 4 V versus metallic lithium, have become attractive as cathodes for Li-ion cells. Most commercial Li-ion cells use a graphite or coke anode and either a $LiCoO_2$ or $LiNiO_2$ cathode or variants with a mixture of both metals. Exhibit 4.5 shows a number of materials which have been investigated as electrodes in Li-ion batteries, and their potentials versus lithium metal.

Although the replacement of metallic lithium having a large capacity of 3,860 mAh/g by carbon with a capacity of just 372 mAh/g results in a sacrifice in specific energy, cells based on the rocking-chair configuration offer significant advantages in terms of cycle life and safety.

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[4] *Lithium Batteries: Science and Technology.* G-A Nazri and G Pistoia (Eds). Kluwer Academic Press (Massachusetts) 2004

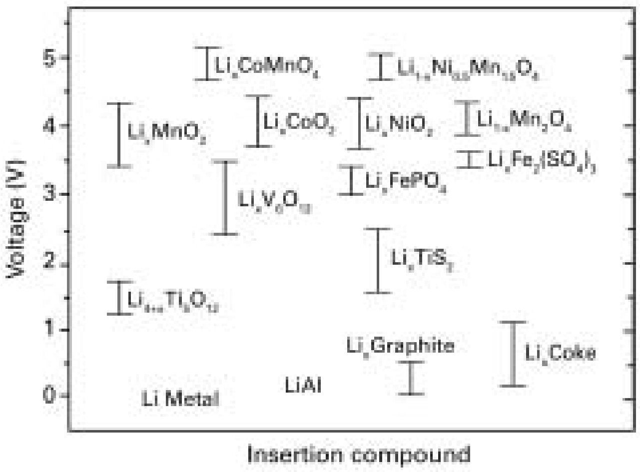

Exhibit 4.5 Electrochemical potential ranges of some lithium insertion compounds versus lithium metal

The following are important characteristics in the selection of materials for high-performance (high energy and power) commercial Li-ion cells.

The electrodes should have:

- A large degree of lithium insertion/extraction (high capacity)
- High electronic and Li^+ conductivity
- Good structural and chemical stability anodes and cathodes
- Affordable cost

The electrolyte should:

- Have a high Li^+ conductivity and be electronically insulating
- Be electrochemically and chemically stable towards the electrodes
- Be affordable

In addition, cell safety, environmental factors and raw materials and fabrication costs are other important factors to consider in materials selection and cell design.

4.1.3 Types of commercial Li-ion batteries

There are two types of Li-ion cells which are commercially available. These are conventional Li-ion batteries and Li-ion-polymer (LIP) batteries.

Conventional Li-ion batteries

Today, Li-ion is the fastest growing and most promising battery chemistry. Its energy density is typically twice that of the standard Ni-Cd. Improvements in electrode active materials have the potential of increasing the energy density close to three times that of Ni-Cd. In addition to high capacity, the load characteristics are reasonably good, and the discharge characteristics are similar to Ni-Cd (similar shape of discharge profile, but different voltage). The flat discharge curve offers effective utilisation of the stored power in a desirable voltage spectrum.

The Li-ion is a low-maintenance battery, an advantage that most other chemistries cannot claim. There is no ‘memory’, and no scheduled cycling is required to prolong the battery’s life. In addition, the self-discharge is less than half compared to Ni-Cd and Ni-MH, making the Li-ion well suited for modern fuel-gauge applications.

The high cell voltage of Li-ion allows the manufacture of battery packs consisting of only one cell. Many of today’s mobile phones run on a single cell, an advantage that simplifies battery design. Supply voltages of electronic applications have been decreasing, which in turn requires fewer cells per battery pack. To maintain the same power, however, higher currents are needed. This emphasises the importance of very low cell resistance to allow unrestricted flow of current.

During recent years, several types of Li-ion batteries have emerged with only one thing in common — the catchword 'lithium'. Although strikingly similar on the outside, lithium-based batteries can vary widely. This section addresses the lithium-based batteries that are predominantly used in commercial products.

Sony’s original version of the Li-ion battery used coke, a product of coal, as the negative electrode. Since 1997, most Li-ion batteries (including Sony's) have shifted to graphite. This electrode provides a flatter discharge voltage curve than coke and offers a sharp 'knee-bend' at the end of discharge. As a result, the graphite system delivers the stored energy by only having to discharge to 3.0 V/cell, whereas the coke version must be discharged to 2.5 V to get similar run-time. In addition, the graphite version is capable of delivering a higher discharge current and remains cooler during charge and discharge than the coke version.

For the positive electrode, two distinct chemistries have emerged. They are cobalt and spinel (also known as manganese). Whereas cobalt has been in use longer, spinel is inherently safer and more forgiving if abused. Small prismatic spinel packs for mobile phones may only include a thermal fuse and temperature sensor. In addition to cost savings on a simplified protection circuit, the raw material cost for spinel is lower than that of cobalt.

As a trade-off, spinel offers a slightly lower energy density, suffers capacity loss at temperatures above 40ºC, and ages quicker than cobalt.

The choice of metals, chemicals and additives helps balance the critical trade-off between high energy density, long storage time, extended cycle-life and safety. High energy densities can be achieved with relative ease. For example, adding more nickel in lieu of cobalt increases the ampere/hours rating and lowers the manufacturing cost but makes the cell less safe. While a start-up company may focus on high energy density to gain quick market acceptance, safety, cycle-life and storage capabilities may be compromised. Reputable manufacturers, such as Sony, Panasonic, Sanyo, Moli Energy and Polystor place high importance on safety. Regulatory authorities assure that only safe batteries are sold to the public.

Li-ion cells cause less harm when disposed of than lead- or cadmium-based batteries. Among the Li-ion family, spinel is the friendliest in terms of disposal.

Despite its overall advantages, Li-ion also has its drawbacks. It is fragile and requires a protection circuit to maintain safe operation. Built into each pack, the protection circuit limits the peak voltage of each cell during charge and prevents the cell voltage from dropping too low on discharge. In addition, the maximum charge and discharge current is limited and the cell temperature is monitored to prevent temperature extremes. With these precautions in place, the possibility of metallic lithium plating occurring due to overcharge is virtually eliminated.

Ageing is a concern with most Li-ion batteries. For unknown reasons, battery manufacturers are silent about this issue. Some capacity deterioration is noticeable after one year, whether the battery is in use or not. Over two or perhaps three years, the battery frequently fails. It should be mentioned that other chemistries also have age-related degenerative effects. This is especially true for the Ni-MH if exposed to high ambient temperatures.

Storing the battery in a cool place slows down the ageing process of the Li-ion (and other chemistries). Manufacturers recommend storage temperatures of 15ºC. In addition, the battery should only be partially charged when in storage.

Extended storage is not recommended for Li-ion batteries. Instead, packs should be rotated. The buyer should be aware of the manufacturing date when purchasing a replacement Li-ion battery. Unfortunately, this information is often encoded in an encrypted serial number and is only available to the manufacturer.

Manufacturers are constantly improving the chemistry of the Li-ion battery. Every six months, a new and enhanced chemical combination is tried. With such rapid progress, it becomes difficult to assess how well the revised battery ages and how it performs after long-term storage.

The most economical lithium-based battery in terms of cost-to-energy ratio is a pack using the cylindrical 18650 cell. This battery is somewhat bulky but suitable for portable applications such as mobile computing. If a slimmer pack is required (thinner than 18 mm), the prismatic Li-ion cell is the best choice. There is little or no gain in energy density per weight and size over the 18650; however, the cost is more than double.

If an ultra-slim geometry is needed (less than 4 mm), the best choice is Li-ion-polymer. This is the most expensive option in terms of energy cost. The Li-ion-polymer does not offer appreciable energy gains over conventional Li-ion systems, nor does it match the durability of the 18650 cell.

Li-ion-polymer (LIP) batteries

The LIP battery differentiates itself from other systems in the type of electrolyte used. The original design, dating back to the 1970s, uses a dry solid polymer electrolyte only. This electrolyte resembles a plastic-like film that does not conduct electricity but allows exchange of ions. The polymer electrolyte replaces the traditional porous separator, which is soaked with electrolyte.

The dry polymer design offers simplifications with respect to fabrication, ruggedness, safety and thin-profile geometry. There is no danger of flammability because no liquid or gelled electrolyte is used.

With a cell thickness measuring as little as 1 mm, equipment designers are left to their own imagination in terms of form, shape and size of cells. It is possible to create designs which form part of a protective housing, are in the shape of a mat that can be rolled up, or are even embedded into a carrying case or piece of clothing. Such innovative batteries are still a few years away, especially for the commercial market.

Unfortunately, the dry LIP suffers from poor conductivity. Internal resistance is too high and cannot deliver the current bursts needed for modern communication devices and spinning-up the hard drives of mobile computing equipment. Although heating the cell to 60°C and higher increases the conductivity to acceptable levels, this requirement is unsuitable in commercial applications.

Research is continuing to develop a dry solid LIP battery that performs at room temperature, and a version is expected to be commercially available during 2005. It is expected to be very stable; would run 1,000 full cycles, and would have higher energy densities than today’s Li-ion battery.

In the meantime, some LIP batteries are used as stand-by batteries in hot climates. One manufacturer has added heating elements that keep the battery in the conductive temperature range at all times. Such a battery performs well for the application intended because a high ambient temperature does not affect the service life of this battery in the same way it does a VRLA battery, for example.

To make a small LIP battery conductive, some gelled electrolyte has been added. Most of the commercial LIP batteries used today for mobile phones are hybrids, containing gelled electrolyte. While the correct term for this system is ‘Li-ion-polymer’, for promotional reasons most battery manufacturers mark the battery simply as ‘Li-polymer’. Since the hybrid LIP battery is the only functioning polymer battery for portable use today, this section will focus on this chemistry.

With gelled electrolyte added, what then is the difference between Li-ion and LIP? Although the characteristics and performance of the two systems are very similar, the LIP is unique in that it uses a solid electrolyte, replacing the porous separator. The gelled electrolyte is simply added to enhance ion conductivity.

Technical difficulties and delays in volume manufacturing have deferred the introduction of the LIP battery. This postponement, as some critics argue, is due to ‘cashing-in’ on the Li-ion battery. Manufacturers have invested heavily in R&D and equipment to mass-produce the Li-ion battery. Now businesses and shareholders want to see a return on their investment.

In addition, the promised superiority of the LIP has not yet been realised. No improvements in capacity gains have been achieved – in fact, the capacity is slightly less than that of the standard Li-ion battery. For the present, there is no cost advantage in using the LIP battery. The thin profile has, however, compelled mobile phone manufacturers to use this promising technology for their new-generation handsets.

One of the advantages of the LIP battery, however, is simpler packaging – because the electrodes can easily be stacked. Foil packaging, similar to that used in the food industry, is being used. No defined norm in cell size has been established by the industry.

4.1.4 Cell construction and battery configuration

Cylindrical cells

The cylindrical cell continues to be the most widely used packaging style. The advantages are ease of manufacture and good mechanical stability. The cylinder has the ability to withstand high internal pressures. A venting system is added on one end of the cylinder. Venting occurs if the cell pressure reaches a set limit.

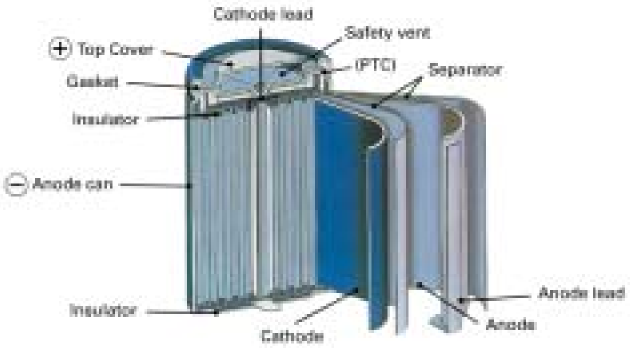

Exhibit 4.6 Internal construction of a cylindrical Li-ion cell

Exhibit 4.6 illustrates the construction of a conventional cylindrical Li-ion cell.

The cylindrical cell is moderately priced and offers high energy density. Typical applications are wireless communication, mobile computing, biomedical instruments, power tools and other uses that do not demand ultra-small size.

Ni-Cd offers the largest selection of cylindrical cells. A good variety is also available in the Ni-MH family, especially in the smaller cell formats. In addition to cylindrical formats, Ni-MH also comes in prismatic cell packaging.

Li-ion batteries are only available in limited cell sizes, the most popular being the 18650. ‘Eighteen’ denotes the diameter in millimetres and ‘65’ describes the length in millimetres. The 18650 cell has a capacity of 1,800 to 2,200 mAh. The larger 26650 cell has a diameter of 26 mm and delivers 3,200 mAh. Because of the flat geometry of the LIP, this battery chemistry is not available in a cylindrical format.

The drawback of the cylindrical cell is less than maximum use of space. When stacking the cells, air cavities are formed. Because of fixed cell size, the pack must be designed around the available cell size.

Almost all cylindrical cells are equipped with a venting mechanism to expel excess gases in an orderly manner. Whereas nickel-based batteries feature a resealable vent, many cylindrical Li-ion contain a membrane seal that ruptures if the pressure exceeds 3,448 kPa (500 psi). There is usually some serious swelling of the cell before the seal breaks. Venting only occurs under extreme conditions.

Button cells

The button cell (Exhibit 4.7) was developed to miniaturise battery packs and solve stacking problems. Today, this architecture is limited to a small niche market. Non-rechargeable versions of the button cell continue to be popular and can be found in watches, hearing aids and memory backup.

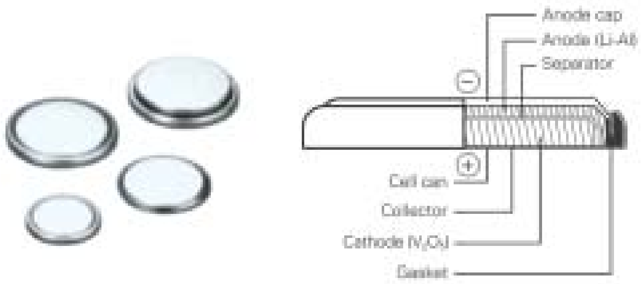

Exhibit 4.7 Button cell

The main applications of the rechargeable button cell are (or were) older cordless telephones, biomedical devices and industrial instruments. Although small in design and inexpensive to manufacture, the main drawback is swelling if charged too rapidly. Button cells have no safety vent and can only be charged at a 10 to 16 hour charge rate. New designs claim rapid charge capability.

Prismatic cells

The prismatic cell was developed in response to consumer demand for thinner pack sizes. Introduced in the early 1990s, the prismatic cell makes almost maximum use of space when stacking. Narrow and elegant battery styles are possible that suit today's slim-style geometry. Prismatic cells are used predominantly for mobile phone applications. Exhibit 4.8 (a) shows a range of Sony's prismatic cells.

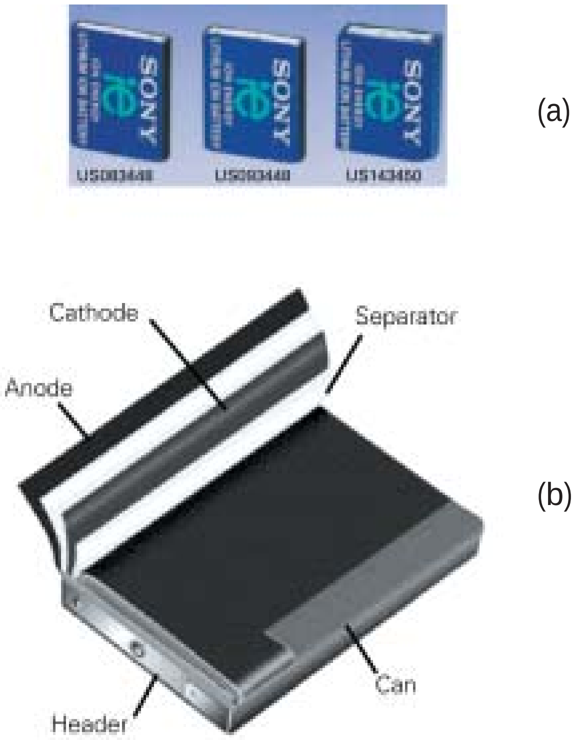

Exhibit 4.8 (a) Sony prismatic cells; (b) cross-section of a prismatic cell

Prismatic cells are most common in the lithium battery family. The LIP is exclusively prismatic. No universally accepted cell size exists for LIP batteries. One leading manufacturer may bring out one or more sizes that fit a certain portable device, such as a mobile phone. While these cells are produced at high volume, other cell manufacturers follow suit and offer an identical cell at a competitive price. Prismatic cells that have gained acceptance are the 340648 and the 340848. Measured in millimetres, '34' denotes the width, '06' or

'08' the thickness and '48' the length of the cell.

Some prismatic cells are similar in size but vary by just a small fraction. Such is the case with the Panasonic cell that measures 34 mm by 50 mm and is 6.5 mm thick. If a few cubic millimetres can be added for a given application, the manufacturer will do so for the sake of higher capacity.

The disadvantage of the prismatic cell is slightly lower energy density compared to the cylindrical equivalent. In addition, the prismatic cell is more expensive to manufacture and does not provide the same mechanical stability enjoyed by the cylindrical cell. To prevent bulging when pressure builds up, heavier gauge metal is used for the container. The manufacturer allows some degree of bulging when designing the battery pack.

The prismatic cell is offered in limited sizes and chemistries, and runs from about 400 mAh to 2,000 mAh and higher. Because of the very large quantities required for mobile phones, special prismatic cells are built to fit certain models. Most prismatic cells do not have a venting system. In case of pressure build-up, the cell starts to bulge. When correctly used and properly charged, no swelling should occur.

Pouch cells

Cell design made a profound advance in 1995 when the 'pouch cell' concept was developed. Rather than using an expensive metallic cylinder and glass-to-metal electrical feed-through to insulate the opposite polarity, the positive and negative plates are enclosed in flexible, heat-sealable foils. The electrical contacts consist of conductive foil tabs that are welded to the electrode and sealed to the pouch material. Exhibit 4.9 illustrates the pouch cell.

Exhibit 4.9
Pouch cell

The pouch cell concept allows tailoring to exact cell dimensions. It makes the most efficient use of available space and achieves a packaging efficiency of 90 to 95%, the highest among battery packs. Because of the absence of a metal can, the pouch pack has a lower weight. The main applications are mobile phones and military devices. No standardised pouch cells exist, but rather, each manufacturer builds to a special application.

The pouch cell is exclusively used for Li-ion and LIP chemistries. At the present time, it costs more to produce this cell architecture, and its reliability has not been fully proven. In addition, the energy density and load current are slightly lower than that of conventional cell designs. The cycle life in everyday applications is not well documented but is, at present, less than that of the Li-ion system with conventional cell design.

A critical issue with the pouch cell is the swelling that occurs when gas is generated during charging or discharging. Battery manufacturers insist that Li-ion or polymer cells do not generate gas if properly formatted, are charged at the correct current and are kept within allotted voltage levels. When designing the protective housing for a pouch cell, some provision for swelling must be made. To alleviate the swelling issue when using multiple cells, it is best not to stack pouch cells, but lay them side by side.

The pouch cell is highly sensitive to twisting. Point pressure must also be avoided. The protective housing must be designed to protect the cell from mechanical stress.

4.1.5 Battery pack configurations

In most cases, a single cell does not provide a high enough voltage, and a serial connection of several cells is needed. The metallic skin of the cell is insulated to prevent the ‘hot’ metal cylinder from creating an electrical short circuit against the neighbouring cell.

Nickel-based cells provide a nominal cell voltage of 1.25 V. LA cells deliver 2 V, and most Li-ion cells are rated at 3.6 V. The spinel (manganese) and LIP systems sometimes use 3.7 V as the designated cell voltage. This is the reason for the often unfamiliar voltages, such as 11.1 V for a three-cell pack of spinel chemistry.

Nickel-based cells are often marked 1.2 V. There is no difference between a 1.2 and 1.25 V cell; it is simply the preference of the manufacturer in marking. Whereas commercial batteries tend to be identified with 1.2 V/cell, industrial, aviation and military batteries are still marked with the original designation of 1.25 V/cell.

A five-cell nickel-based battery delivers 6 V (6.25 V with 1.25 V/cell marking) and a six-cell pack has 7.2 V (7.5 V with 1.25 V/cell marking). The portable LA comes in three-cell (6 V) and six-cell (12 V) formats. The Li-ion family has either 3.6 V for a single-cell pack, 7.2 V for a two-cell pack, or 10.8 V for a three-cell pack. The 3.6 V and 7.2 V batteries are commonly used for mobile phones; laptops use the larger 10.8 V packs.

There has been a trend towards lower voltage batteries for light portable devices, such as mobile phones. This was made possible through advancements in microelectronics. To achieve the same energy with lower voltages, higher currents are needed. With higher currents, a low internal battery resistance is critical. This presents a challenge if protection devices are used. Some losses through the solid-state switches of protection devices cannot be avoided.

Packs with fewer cells in series generally perform better than those with 12 cells or more. Similar to a chain, the more links that are used, the greater the odds of one breaking. On higher-voltage batteries, precise cell matching becomes important, especially if high-load currents are drawn or if the pack is operated in cold temperatures.

Parallel connections are used to obtain higher ampere-hour (Ah) ratings. When possible, pack designers prefer using larger cells. This may not always be practical because new battery chemistries come in limited sizes. Often, a parallel connection is the only option to increase the battery rating. ‘Paralleling’ is also necessary if pack dimensions restrict the use of larger cells. Among the battery chemistries, Li-ion lends itself best to parallel connection.

4.2 Current status of Li-ion technologies

4.2.1 Li-ion batteries

Of all the battery technologies available today, Li-ion provides the highest gravimetric/volumetric energy density and hence best performance for a given size and weight. As such, it is the preferred technology for use in HEVs. However, the high cost of Li-ion batteries has hindered their use in this application to date. Even though there are a number of development programmes (including the ‘Efficient-C’ Programme in the UK) involving the use of Li-ion batteries in prototype HEVs, the commercial realisation of such vehicles will depend on lowering the cost of Li-ion technology.

Nevertheless, Li-ion is the most versatile of the battery technologies, has the highest specific energy and power, with cells and monoblocs available in a range of sizes from different manufacturers. The main manufacturers of cells and modules of sizes suitable for HEV requirements are Saft UK and Saft USA.

Saft manufactures a range of cells and modules for high-energy to high-power applications, and has experience in qualifying and testing batteries for civil, military and space applications. The cells are available in three main sizes – the VL 45 E series, the VL 30 M series and the VL 8-30 P series – catering for high-energy, medium-energy (medium-power) and low-energy (high-power) requirements respectively. Saft has been involved in a number of European and international EV/HEV programmes, including initiatives sponsored by the EU and national governments (Joule-Thermie, EV LIFT, PCRD) and the programme funded by the US Advanced Battery Consortium (USABC) since 2002 as part of FreedomCAR activities in the USA (see Section 12.1.2).

Li-ion batteries have been cycled and successfully road-tested in a number of demonstration vehicles including the Peugeot 106 platform, the CR Fiat Seicento and various DaimlerChrysler vehicles.

Most of the DOE national laboratories and military laboratories visited during the mission (including SNL, NREL and DARPA) are using Saft batteries in the development of their HEV vehicles. No new battery technologies are currently being examined for HEV applications.

A breakdown of the manufacturing cost of typical commercial Li-ion 18650 cells is given in Exhibit 4.10.

Item	Cost ($)	% of total cost
Cathode ($LiCoO_2$)	0.62	34.4
Separator	0.14	7.8
Electrolyte	0.30	16.7
Anode	0.24	13.3
Overheads and direct labour	0.50	27.8
Total manufacturing cost	1.8	100

Exhibit 4.10 Rough estimate of manufacturing costs of Li-ion 18650 based on $LiCoO_2$ ($LiCoO_2$ = $40/kg)

As can be seen, the cathode contributes significantly to the cost of the cell, hence research has focused on trying to find cheaper alternatives without compromising safety and performance. Cheaper cathodes with better cycle-life have been obtained by substituting some of the cobalt in the structure with nickel and manganese in the cathode structure[5,6]. Unfortunately, this only results in marginal improvements in cycle-life and gravimetric/volumetric energy density, with safety being compromised. Other metals like aluminium and even magnesium have also been substituted in the cathode structure in order to increase the amount of lithium that can be extracted from the cathode structure and hence energy density, but with little success. The majority of the research work on these mixed cathodes is being undertaken by Japanese/Korean companies, and an Li-ion battery based on the $LiCo_{0.33}Ni_{0.33}Mn_{0.33}O_2$ cathode may soon be commercially available.

LIP systems may be intrinsically safer than their Li-ion counterparts but suffer from poorer performance and higher cost in the volumes that they are being produced currently. Higher volume production may reduce the purchase costs of polymer-based systems below that of current Li-ion systems.

The improvements in the energy density of Li-ion cells which have been seen in the last five years or so can be attributed mainly to improved construction rather than novel advanced battery electrode materials.

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[5] W Li and J Curie, *J Electrochem Soc* 144: 2773 (1997)

[6] Y Shin and A Manthiram, *Electrochem Solid-State Lett* 6: A34 (2002)

The control electronics which are used to improve safety in Li-ion battery packs are often complex and can contribute significantly to the overall cost of the battery. Using safer cathode materials may help to simplify or even eliminate the need for electronics, and hence reduce the cost of Li-ion batteries. It is with this in mind that alternative cathode systems based on manganese have been investigated. Unfortunately, there is a compromise in performance, as can be seen from Exhibit 4.11, and research on these cathode materials has generally been scaled down.

	Cobalt	Manganese (spinel)
Energy density (Wh/kg)	140	120
Safety	On overcharge, the Co electrode provides extra Li, which can form into metallic Li, causing a potential safety risk if not protected by a safety circuit	On overcharge, the Mn electrode runs out of Li, causing the cell only to get warm. Safety circuits can be eliminated for small 1- and 2-cell packs
Temperature	Wide temperature range. Best suited for operation at elevated temperature	Capacity loss above +40ºC. Not as durable at higher temperatures
Ageing	Short-term storage possible. Impedance increases with age. Newer versions offer longer storage	Slightly less than Co. Impedance changes little over the life of the cell. Due to continuous improvements, storage time is difficult to predict
Life expectancy	300 cycles, 50% capacity at 500 cycles	May be shorter than Co
Cost	Raw material relatively high. Protection circuit adds to costs	Raw material 30% lower than Co. Cost advantage on simplified protection circuit

Exhibit 4.11 Comparison of properties of Co- and Mn-based cathode materials

4.2.2 Lithium-iron phosphate batteries

Valence Technology Inc of Austin, Texas, is currently developing rechargeable batteries for portable, HEV, stationary and large applications based on lithium-iron phosphate cathode ('Saphion') technology. The major drivers for this technology are safety and the environment. The performance of an 18650 prototype cell based on this new cathode material has been demonstrated (Exhibit 4.12).

	$LiCoO_2$	$LiFePO_4$
Form factor (mm)	18x65	18x65
Nominal voltage (V)	3.6	3.2
Nominal capacity (mAh)	2,200	1,450
Energy density	450 Wh/ℓ 175 Wh/kg	280 Wh/ℓ 120 Wh/kg
Life-cycle range	100-500	1,000-2,000
Approximate cell cost ($)	4.00	5.00
Power cost ($/Wh)	0.51	1.07
Safety	Average	Very good
'Green' rating	Average	Good
C-rate	Low	Medium

Exhibit 4.12 Comparison of commercial $LiCoO_2$ 18650 with a Valence Technology Inc $LiFePO_4$ prototype

Li-ion batteries based on this new cathode material have the advantage over the current Li-ion batteries of being safer, with a 40% increase in cycle-life at similar depth of discharges resulting in a lower through-cycle-life cost. The specific energy for these battery systems is slightly higher than that for the current Li-ion batteries (170 Wh/kg, compared to 150 Wh/kg for Li-ion batteries) but the initial purchase cost is also estimated to be higher due to the expensive material synthesis routes for the lithium-iron phosphate cathode. LIP cells based on Valence Technology's lithium-iron phosphate cathodes are available commercially, and the use of small 18650 cells with organic liquid electrolytes has been demonstrated in a number of portable applications. Timescale to market for larger cells based on this technology is around 2-3 years.

4.2.3 Lithium-sulphur batteries

Sion Power, based in Tucson, Arizona, is developing Li-S rechargeable battery chemistry in pouch-cell format. Sion Power is a spin-off from Brookhaven National Laboratory (BNL), and was founded as Moltech in 1988. The company became known as Sion Power in 2002. Sion Power's technology is of interest due to the high specific energies claimed for the system. A specific energy of 350 Wh/kg has recently been realised for a 2.5 Ah cell. This compares favourably to other Li-ion chemistries that nominally achieve 180 Wh/kg.

Sion Power has recently demonstrated the use of a battery, based on its early generation prototype Li-S cells, to power a PC at a computer hardware conference. This battery was produced using older Li-S technology with cells of 250 Wh/kg. The complete battery pack including containment and control electronics had a specific energy of 175 Wh/kg. This improved upon the 138 Wh/kg for the comparable standard Li-ion battery normally used for this PC. Each cell had a capacity of 1.2 Ah.

The technology has advanced significantly since that demonstration, and current cells being produced achieve 350 Wh/kg. It is felt that this can be increased easily to 400 Wh/kg simply by increasing the cell size from the current 2.5 Ah to 5 Ah, since the parasitic weight of packaging will become less at the larger scale. The assembly machinery to build these larger cells has not been built yet but is planned for the next six months. Improvements in material utilisation are expected to yield batteries with specific energies of 450 Wh/kg by 2006 with the potential to increase further to 600 Wh/kg in the future.

Li-S outperforms standard Li-ion in terms of gravimetric performance but currently lags slightly behind in terms of volumetric performance. Current standard commercial Li-ion achieves around 350 Wh/ℓ, with advanced prototypes achieving 450 Wh/ℓ The current generation of Li-S cells achieves 350 Wh/ℓ. Sion Power expects to improve this value by optimising cell construction, but it is unlikely that the Li-S battery will have a better volumetric performance than Li-ion because of the lower density of the materials used in Li-S technology.

The cathode consists of a blend of sulphur, carbon and binder coated onto an aluminised polymer sheet of 12 µm. The polymer substrate is primed before coating. The polymer is coated on both sides with active material to a thickness of 40 µm.

The anode is currently commercial lithium foil, although there is a desire in the future to move away from this and to use vacuum-deposited lithium on a substrate. The anode and cathodes are separated by a standard Li-ion separator and rolled into a jelly roll. The mandrel for this is not cylindrical, and this aids the formation of a prismatic cell when the jelly roll is pressed into shape. The active material then has tabs added and is placed inside a prismatic metallised plastic packaging. This package then has electrolyte added and is allowed to equilibrate before final sealing, thus removing any gassing problems. The construction is performed in a dry-room, although Sion Power has facilities to fill cells in an inert atmosphere if less-stable electrolytes are used.

Sion Power currently has the capability to produce up to 100 batteries per day, although it has no desire to do this due to R&D constraints.

It is predicted that the cost of a 'productionised' Li-S battery will be about two-thirds that of an Li-ion battery on a normalised Wh basis, due to the cheaper materials being used and the increased specific energy of the chemistry.

The Sion Power Li-S battery is currently at the advanced prototype stage, and is not yet commercialised. However, prototype cells can be purchased for assessment to meet the requirements of specific applications.

A number of issues still remain to be resolved before the batteries can become widely adopted. One of these is the limited cycle-life of the batteries. For the 350 Wh/kg, 2.5 Ah cells, Sion Power is currently achieving only 50 cycles at 100% depth of discharge (DOD). At 50% DOD, 120 cycles have been achieved, and this value is projected to increase to 200 cycles at 20% DOD.

Sion Power expects to improve the cycle-life as research continues. They point out the fact that it is common in the development of new batteries for cycle-life to reduce as the specific energy of a system is initially increased. Cycle-life generally increases as the technology is further developed until the technology is pushed further again to increased specific energies.

The other major issue is one of safety. The Li-S cells use lithium metal, and the safety of the cells will need to be fully qualified before they can achieve widespread use.

Sion Power has a comprehensive safety programme, and has complete data for earlier generations of its cells – the 150 Wh/kg and 250 Wh/kg generations. These cells have passed the UL tests which are consistent with UN tests. The latest generation of 350 Wh/kg cells have not been fully characterised yet, although they have now passed the 150ºC ‘hot-box’ test. Abusive overcharge is currently an issue for these cells but this will be solved by electronic measures. The cells in their current state of development must still be shipped as ‘Class 9’ hazardous materials.

There is currently an air transport limit of 1 g of lithium per cell for any lithium-metal battery. In part, this is the reason why 2.5 Ah cells are being produced, since they contain only 1 g of lithium per cell.

4.2.4 Lithium-metal-polymer (LMP) batteries

LMP batteries are still being developed for EV and HEV applications by Avestor (based at Boucherville, QC, Canada). The LMP-EV batteries are projected to weigh 175 kg, with a power and energy of 42 kW and 21 kWh respectively. 120-200 Wh/kg is achievable. These batteries are expected to be commercially available in 2006 with a similar cost to Li-ion but with greater safety.

Technology development of LMP batteries at Avestor has been going on for the last 25 years, but the manufacturing facility is relatively new (2002). Most of the machinery for this plant is custom-built for the product, and encapsulated in special dry-rooms to protect the lithium during manufacturing.

Exhibit 4.13 Alvestor LMP SE 48S63 battery power module

In September 2004, Avestor launched the SE 48S63 battery power module (Exhibit 4.13) with auto-disconnect. The product is impressive not just for the lithium technology or for the size and weight (a 48 V telecom battery in one 29 kg block) but especially for the integrated intelligent interface. This very clever interface changes a battery storage device into a stand-alone power source that can be rack-mounted and plugged into a common distribution bus. The aspect which is really impressive is the capability to safely short the output with no ill effect. The power source immediately protects itself and the user by silently limiting the output to zero. It sounds so simple but is still unnerving to witness!

4.2.5 LMP pouch cell technology

The Advanced Battery Program at MIT (Department of Materials Science and Engineering) has developed a number of all-solid-state Li-ion cells. These cells are based on lithium anodes with dry block copolymer electrolytes (BCEs) and conventional Li-ion insertion metal oxide cathodes.

The first-generation BCEs consist of poly (oxyethylene methacrylate) – POEM – and poly (alkyl methacrylate) units doped with high concentrations of a lithium salt such as $LiCF_3SO_3$, and have low glass transition temperatures ($T_g < -60^{\circ}C$) and conductivities as high as $\sigma > 1x10^{-6}$ S/cm at room temperature.

In addition, these polymer electrolytes show good chemical stability against lithium metal, have a wide electrochemical window (≤ 5 V against common cathodes), and very good dimensional stability and mechanical integrity. These latter properties enable their fabrication as a very thin (low-resistance) electrolyte layer, hence giving pouch cells a high flexible form factor. A specific energy and specific power of up to 400 Wh/kg (700 Wh/ℓ) and 650 W/kg (11 kW/ℓ) respectively has been achieved in pouch cells with a lithium-metal anode and a lithium-cobalt oxide cathode.

MIT is also developing second-generation polymer electrolytes based on graft copolymer electrolytes (GPEs). A free radical synthesis is used to graft poly (dimethyl siloxane) on the POEM backbone units, resulting in a polymer with a wide electrochemical window, a very low Tg, and $\sigma > 1x10^{-5}$ S/cm at room temperature. These polymer electrolytes have the added advantage of high thermal stability and can be heated up to 300ºC without thermal degradation occurring.

Because of the relatively low conductivities of these dry polymer electrolytes compared with liquid systems, they are considered to be more suitable in applications requiring low current drains. In addition, they have negligible vapour pressure since no liquid is used, and may be suitable for use in medical implants as well as in other biomedical devices. However, the power performance of lithium batteries that utilise these electrolytes can be dramatically improved if they are fabricated as very thin films.

MIT is also looking at high oxidation state transition metal ions such as vanadium, and chromium and molybdenum, as cathodes for rechargeable and primary lithium batteries respectively. Most of this work is being funded by the US Navy's Office of Naval Research (ONR).

4.2.6 Lithium-air and lithium-water rechargeable battery systems

As mentioned previously, the combination of a lithium metal anode with traditional cathodes in a battery system will give the highest specific energy due to the light weight and high electrochemical potential of the lithium. But the use of lithium metal anodes has been avoided because of issues relating to poor cycling and safety. Lithium metal is thermodynamically unstable when in contact with organic electrolytes used in rechargeable lithium batteries, leading to the formation of a solid electrolyte interface (SEI). The plating and stripping of lithium through the SEI in a rechargeable battery system, results in dendrite formation and, consequently, safety and performance issues.

However, PolyPlus Battery Co, based in Berkeley, CA, has developed a novel technique for protecting the lithium with

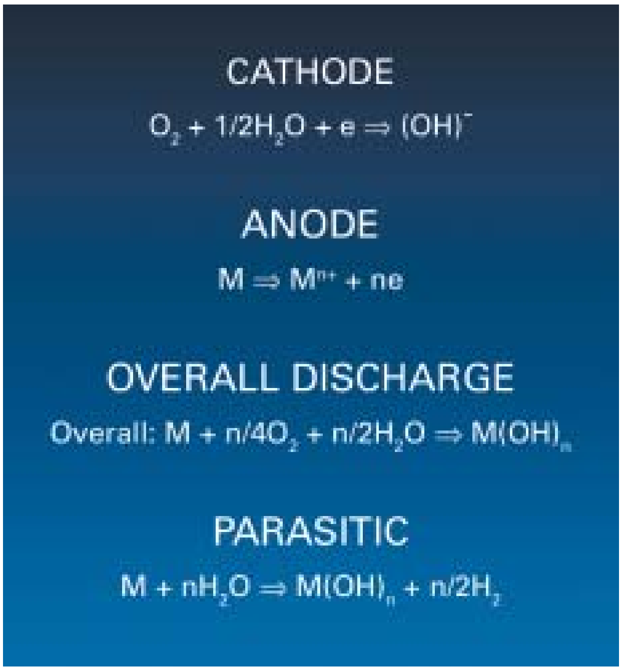
	Li	Mg	Al	Ca	Zn	Fe
Ah/g	3.86	2.21	2.98	1.34	0.82	0.96
Voltage	3.0	1.3	1.3	2.0	1.1	1.0
Wh/kg *(anode)*	11,583	2,867	3,874	2,675	902	960
Wh/kg *(anode +H_2O)*	5,041	1,646	1,935	1,845	902	726
Wh/kg *(end of discharge)*	3,357	1,195	1,340	1,447	725	596

Exhibit 4.14 Comparison of lithium with other potential metal-air systems

a coating which enables a number of revolutionary lithium-based battery chemistries in aqueous media.

Lithium is one of the most promising metal anodes due to its light weight, and PolyPlus is developing lithium-air systems based on the its novel protected electrodes. Exhibit 4.14 highlights the capacity of lithium-air versus some other metal systems.

The reactions which occur in a lithium-air system are shown in Exhibit 4.15. In the case of a protected lithium anode, the parasitic corrosion reaction does not occur.



CATHODE

$O_2 + 1/2H_2O + e \Rightarrow (OH)^-$

ANODE

$M \Rightarrow M^{n+} + ne$

OVERALL DISCHARGE

Overall: $M + n/4O_2 + n/2H_2O \Rightarrow M(OH)_n$

PARASITIC

$M + nH_2O \Rightarrow M(OH)_n + n/2H_2$

Exhibit 4.15 Reactions occurring in a lithium-air system

The PolyPlus process allows a layer of lithium nitride (LiN) to be formed *in situ* on the surface of sputtered lithium (or lithium foil), followed by vacuum sputtering of a very thin layer of Li^+ conducting glass. The combination of the non-porous LiN layer with Li^+ conducting electrolyte, eliminates the electrochemical corrosion of lithium and provides a highly conducting interfacial layer that enables a number of lithium metal battery technologies which were previously difficult or impossible to achieve.

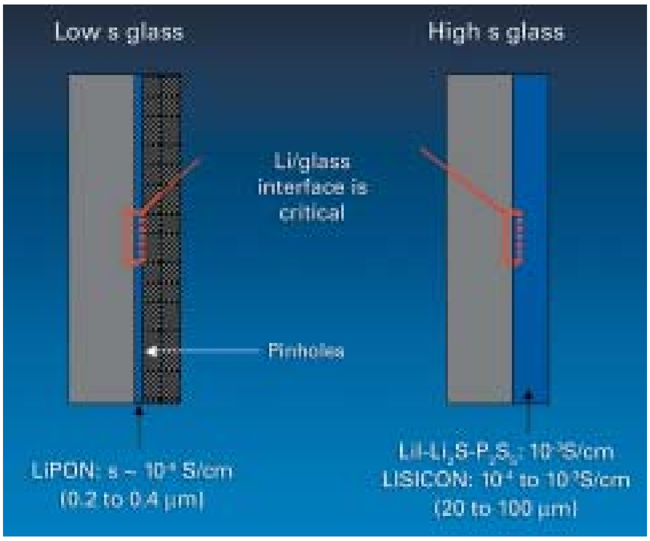


Exhibit 4.16 Lithium-air battery

PolyPlus is focusing on two lithium metal-based technologies. These are Li-air for land applications, and Li-water for marine applications. It is claimed that optimised cells will be capable of providing specific energies of 1,000 Wh/kg. It is initially envisaged that these will be primary cells (ie not rechargeable) but it is expected that the technology could be adapted to secondary (rechargeable) cells with little or no loss in capacity. Test-cells have been constructed and cycled in the laboratory.

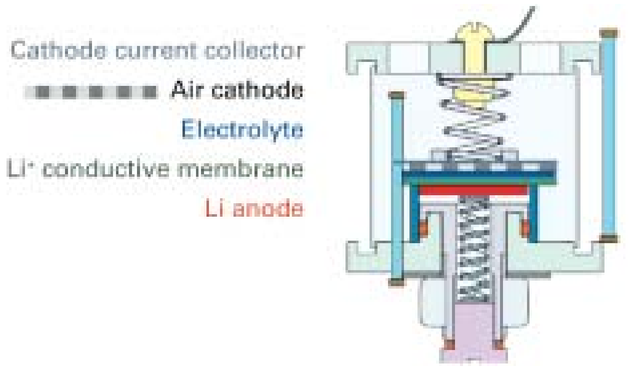


Exhibit 4.17 Test cell construction of lithium-air cell

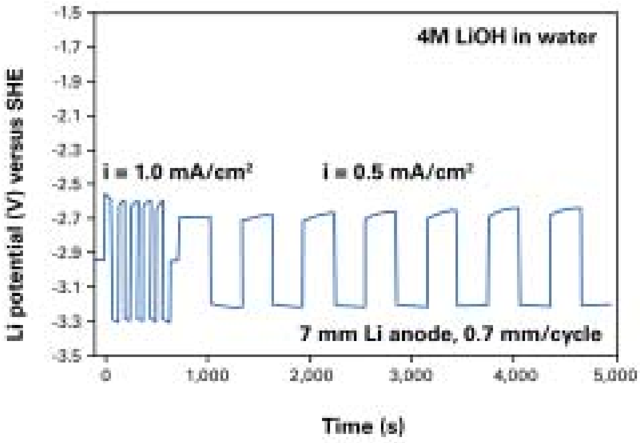


Exhibit 4.18 Cycling of protected lithium anode in aqueous electrolyte

Additional development work would be needed to optimise the air cathode for a rechargeable system, and the lithium hydroxide would need to be held at the cathode to enabling recharging.

This technology is at a much earlier stage of development that Sion Power's Li-S battery, and PolyPlus estimates that it may be another three or four years before it has a battery pack available at a sufficient level of development for assessment by the military. This development time could be shortened if a partner company were found to accelerate the production of batteries from this exciting technology. Development lifetimes are also a function of funding, and if PolyPlus was to receive significant levels of additional funding, this would also accelerate the development time.

PolyPlus has also investigated Li-S chemistry, again utilising its coated lithium anodes. The work is being supported by DOE as a potentially cheap alternative battery chemistry for EV and HEV applications. However, it appears that the lithium-air and lithium-water chemistries are now the major focus of the company. A high voltage of >4 V has also been demonstrated for a lithium-hydrogen peroxide cell.

In summary, PolyPlus has demonstrated the discharge of Li^+ across a Li-water interface at close to 100% coulombic efficiency. The cells have shown excellent discharge rate capability, up to 2 mA/cm^2, with a flat discharge profile, in neutral and acidic electrolytes. The remarkable performance of protected lithium anodes enables the development of a new generation of lithium battery chemistries with potentially exceptional energy density.

PolyPlus is currently developing rechargeable lithium battery systems based on the Li-air and Li-water chemistries. First cycle specific energies of up to 1,000 Wh/kg have been demonstrated in laboratory cells, but this technology is still at the research level.

4.2.7 Lithium-iron disulphide batteries

Currently being developed by QinetiQ Haslar in the UK, lithium-iron disulphide batteries have the potential to match Li-ion batteries on power, but with nearly twice the specific energy at a fraction (one-quarter) of the cost, and a lower voltage of 2.2 – 2.5 V. This material is also intrinsically safer than cathodes used in standard Li-ion batteries.

Lithium-iron disulphide (Li_2FeS_2) has recently been synthesised at QinetiQ via a low- to medium-temperature route (QinetiQ patent) and has the potential to replace $LiCoO_2$ as the cathode of choice in rechargeable Li-ion systems for portable and large applications. This material has the advantage that it is cheaper than $LiCoO_2$ with nearly three times the theoretical specific energy, is environmentally benign, and is virtually unreactive when overcharged.

These advantages translate into:

- Smaller and lighter battery due to higher specific energy
- Less complicated safety/control electronics leading to lower cost
- Lower cost due to higher intrinsic energy content
- Less-stringent safety regulations (with regard to transportation, installation and disposal)

Since Li_2FeS_2 is a solid, there is the further advantage that lightweight envelope cell packaging of the ‘pouch’ type can be used, leading to higher practical specific energy. Preliminary results from laboratory cells suggests that 40% of the theoretical capacity can be extracted from the unoptimised Li_2FeS_2 cathode material, and previous results at QinetiQ have shown that prototype packet cells and laboratory cells give similar results. These results are encouraging, as they imply a 50% decrease in the cost of an HEV battery based on Li_2FeS_2 cathode compared with the current Li-ion systems, even at this early stage of development.

4.3 Key messages

- Most battery research is still aimed at higher energy (rather than power) batteries

- Research on improved performance, lower cost and safer cathode materials for lithium rechargeable batteries is similar for US and UK organisations

- However, UK research on battery technologies is seriously underfunded

- There is a need to establish more collaborative efforts between work in the USA and the UK

- Saft’s high-power Li-ion technology appears to be the battery system of choice for HEV and EV military, commercial and civil applications

- No innovative research on Li-ion rechargeable insertion cathode or anode materials is currently being undertaken

The current status and recent advances in Li-ion technologies in comparison with other rechargeable battery technologies are summarised in tabular form in Appendix D.

Cathode	Reaction	MW (g/mol)	Electrons	Capacity (C/g)	Capacity (mAh/g)	Voltage (V)	Specific energy (Wh/kg) cathode
Li_2FeS_2	$Li_2FeS_2 \rightarrow$ 2Li+ FeS_2	133.85	2	1,442	400	2.5	1,000
$LiCoO_2$	$LiCoO_2 \rightarrow$ 0.5Li+ $Li_{0.5}CoO_2$	97.87	1/2	493	137	3.6	493

Exhibit 4.19 Comparison of characteristics of Li_2FeS_2 and $LiCoO_2$ cathodes

5 NICKEL-METAL HYDRIDE BATTERY TECHNOLOGIES

The launch of the FreedomCAR Partnership in 2002 (see Section 12.1.2) – a US government-industry programme for the advancement of high-efficiency vehicles, built on the activities of the Hybrid Electric Vehicle (HEV) Program that commenced a decade earlier. The five-year, cost-shared HEV Program was a partnership between the DOE and the three largest American auto manufacturers: General Motors, Ford, and DaimlerChrysler. The 'Big Three' committed to produce production-feasible HEV propulsion systems by 1998, first-generation prototypes by 2000, and market-ready HEVs by 2003.

Theoretically, fuel cells may be a cleaner and more efficient power source for HEVs and EVs but they are not currently at a technology readiness level that would enable their use.

Commercially-available HEVs use batteries based on Panasonic's Ni-MH technology. The 2000 Honda Insight uses 120 sealed Ni-MH batteries and has an output power and voltage of 10 kW and 144 V respectively. The 2001 Toyota Prius has an output power and voltage of 33 kW and 273.6 V respectively and uses 228 Ni-MH cells.

Exhibit 5.1 Cobasys Ni-MH HEV battery pack

Panasonic is the main developer of Ni-MH battery technology for HEV applications, and a high-power variant of Ni-MH cells specially designed for HEVs has recently been announced.

Cobasys (formerly Texaco Ovonic), based in Troy, MI, is also developing Ni-MH battery modules for HEV applications (Exhibit 5.1).

Cobasys offers a range of cell modules and battery packs for low-power (high-energy) to high-power HEV applications. It also offers products in the intermediate power/energy range. The battery systems are fully integrated, including battery modules, air-cooled system, packaging, wiring, thermal management electronics, control algorithms, communications bus and pressure regulation. The specifications for the Cobasys HEV battery packs are given in Exhibit 5.2.

Model	NiMHax 144-30	NiMHax 144-60	NiMHax 288-60	NiMHax 288-120
Voltage (V)	144	144	288	288
Capacity (Ah)	8.5	17	8.5	17
Power (kW)	30	60	60	120
Energy (kWh)	1.2	2.4	2.4	4.8
Weight (kg)	45	90	75	150
L x W x H (mm)	430 x 850 x 210	(2) NiMHax 144-30	430 x 850 x 210	(2) NiMHax 288-60

Exhibit 5.2 Characteristics of Cobasys Ni-MH battery modules for HEV applications

6 ULTRACAPACITOR TECHNOLOGIES

A note on terminology may be helpful here: while there is no accepted convention, it appears that the European term 'supercapacitor' and the US 'ultracapacitor' (often abbreviated to ultracap) are equivalent and interchangeable. In this report, the term 'ultracapacitor' has been used throughout for consistency.

6.1 Ultracapacitor technology

Ultracapacitors are a relatively new ES technology, well-suited for applications needing repeated bursts of power for times varying between fractions of a second to several minutes. Ultracapacitors are capable of storing up to 100 times more energy than a conventional capacitor, and can achieve power densities an order of magnitude greater than many batteries.

Ultracapacitors fill an ES 'niche' between normal capacitors, but below batteries, as shown in Exhibit 6.1 Ultracapacitors have the further advantage over batteries of charge-up and discharge times that are measured in seconds rather than hours. A typical LA

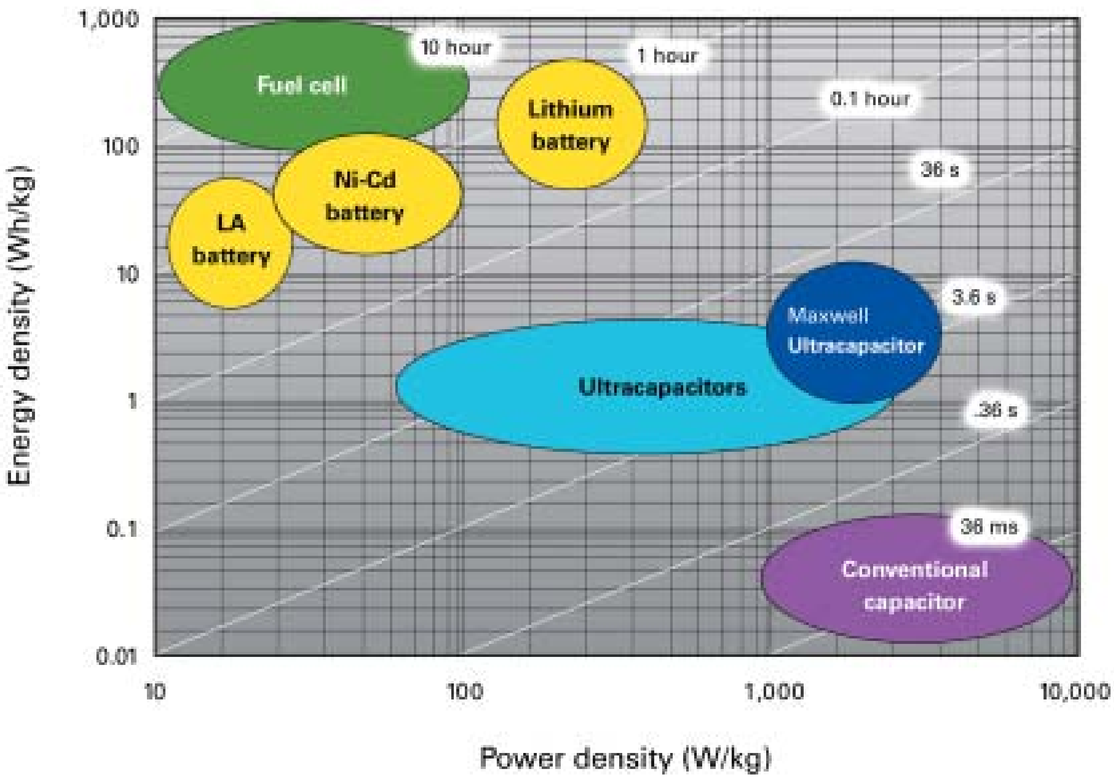


Exhibit 6.1 Energy-density/power-density relationship and recharging time for various ES technologies

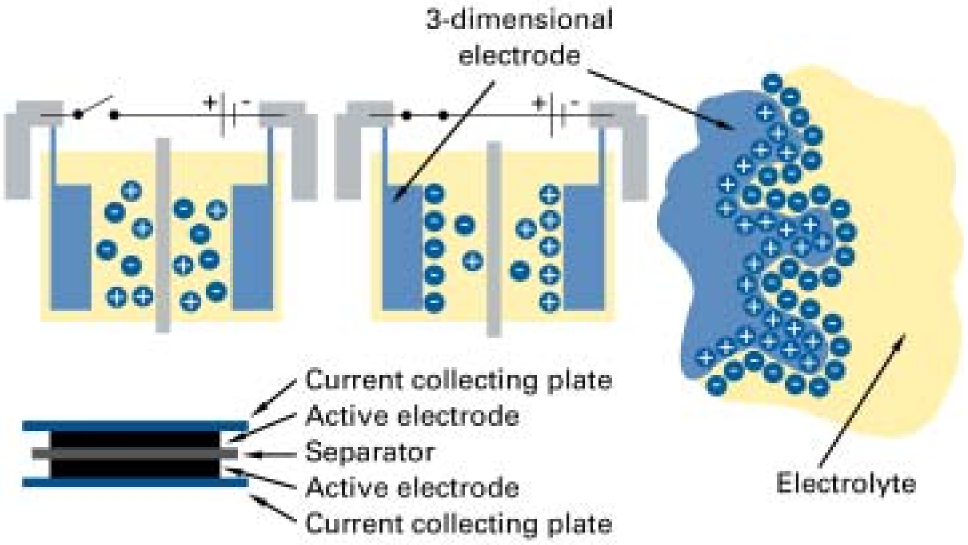


Exhibit 6.2 Double-layer ultracapacitor

battery can take several hours to recharge, compared with around 5 s for an ultracapacitor, as indicated in Exhibit 6.1.

Ultracapacitor voltage levels tend to be lower than those of most batteries, and are in the range 2-3 V. This brings a slight disadvantage in that for higher-voltage applications, a string of ultracapacitors has to be used in series. When this is done, precautions have to be taken to ensure that no ultracapacitor within the string experiences an over-voltage. This subject is further discussed later.

Ultracapacitors store electricity by physically separating positive and negative charges. A battery stores energy chemically. The fact that no chemical events take place within an ultracapacitor means that ultracapacitors do not undergo the degradation processes experienced by most batteries, giving ultracapacitors a much longer shelf- and operating life. It also allows them to operate in colder and hotter environments than most batteries. Figures quoted by Maxwell Technologies during the mission were from –50 to +60ºC.

This combination of features is opening up many applications for ultracapacitors. Although ultracapacitor technology has been available for a number of years, the steady reduction in cost has now brought it within the reach of a very large number of applications where short-term, high power density ES is required.

6.1.1 Cell construction

An ultracapacitor consists of two activated carbon electrodes immersed in an organic electrolyte. The two electrodes are separated by a membrane which allows ionic mobility but prevents electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other when an electrical charge is applied. In the charged state, anions and cations are located close to the electrodes, and balance excess charge in the activated carbon. Thus, across the carbon-electrolyte boundary, two charged layers of opposing polarity are formed as shown in Exhibit 6.2. This effect, discovered in 1879 by Helmholtz, is called an ‘electrochemical double-layer’.

Ultracapacitors rely therefore on an electrostatic effect, which is purely physical and therefore reversible. Charge and discharge occurs upon movement of ions within the electrolyte. This ES process is fundamentally different in character to battery technologies, which are based on chemical reactions. Consequently, an ultracapacitor has several operational advantages when compared to a battery:

- Long shelf-life
- Extended useful life
- High cycle-life

These characteristics imply that an ultracapacitor is a largely maintenance-free ES device.

Double-layer capacitors are either assembled by winding or by stacking in-parallel assemblies of electrodes, current collectors and separator foils. For the stacking process, separate electrode and collector foils are assembled in the device. In this case, it is important to have a very good mechanical contact between the electrode and the current collector. By applying a controlled high pressure on the stack, low internal resistance can be obtained. The disadvantage of the stacking approach to ultracapacitor manufacture is inherently low productivity, and therefore higher production costs. However, stacked devices do allow prismatic designs to be manufactured, which can be extremely space-efficient.

Manufacturers assembling electrodes deposited directly onto a current collector usually use a winding process. The advantage of the winding technique is that it offers a very reliable process, high productivity and therefore low costs. Maxwell Technologies has many years of experience in the winding technology, and, in addition to ultracapacitor manufacture, produces winding machines.

An ultracapacitor offers very high capacitance in a small package. As discussed previously, ES in an ultracapacitor results from movement of static charge, rather than from an electrochemical process as in a battery. Applying a voltage differential to the positive and negative plates recharges the ultracapacitor. As discussed earlier, an ultracapacitor is a double-layer capacitor, with conventional designs based upon a metal/carbon electrode and a non-aqueous electrolytic solution, as shown in Exhibit 6.2. As voltage is applied across the terminals, ions migrate to the high-surface area electrodes. The combination of available surface area and proximity to the current collector provides an ultra-high capacitance for this electrostatic process.

Ultracapacitors store and release electrical energy quickly, efficiently and reliably. They perform well in harsh conditions. Their cycle lifetimes are orders of magnitudes greater than those of batteries, so they do not need to be replaced as often. They are well suited to delivering a lot of power very quickly, and costs have reduced rapidly in recent years and seem likely to continue to fall. Ultracapacitors should not be used to replace batteries: they cannot store enough energy to be the sole source of electrical energy in, for example, an EV or HEV. Rather, ultracapacitors should be viewed as providing a good complement to batteries and other energy sources, providing temporary ES and short-term high-power discharge, as shown in Exhibit 6.3.

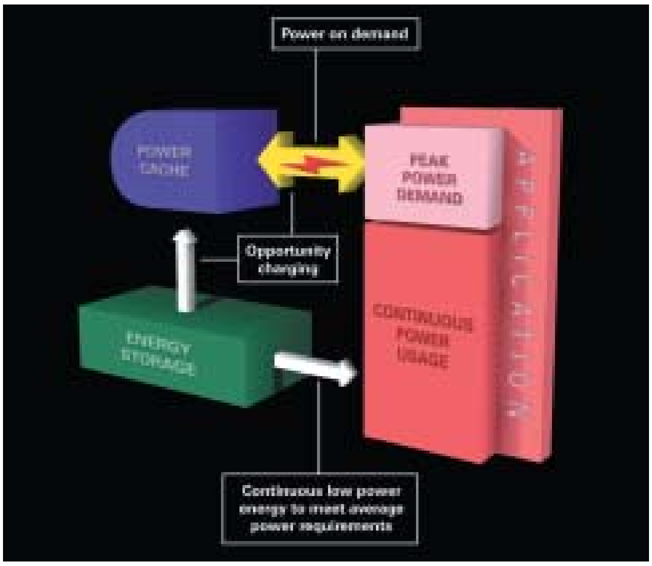


Exhibit 6.3 Typical ultracapacitor application

In a typical application, the ultracapacitor 'caches' power from an energy source. This power is then discharged from the ultracapacitor at rates demanded by the application. The ultracapacitor can be repeatedly charged and discharged at rates optimised for the application. Using ultracapacitors for power bursts in this way optimises the life and efficiency of the system's energy source. The use of an ultracapacitor allows the system to be optimally tailored to meet both power and energy requirements.

A conventional capacitor consists of conductive foils and a dry separator. An ultracapacitor by contrast shares many features with battery technology, since ultracapacitors use special electrodes and an electrolyte. Three types of electrode material are used in conventional ultracapacitor designs. These are: high surface area activated carbons, metal oxides, and conducting polymers. The high surface area electrode approach – sometimes also called a double-layer capacitor (DLC) – is least costly to manufacture and is the most common. In this design, energy is stored in the double-layer formed near the carbon electrode surface.

The electrolyte may be aqueous or organic. The aqueous variety offers low internal resistance but limits the voltage to around 1 V. In contrast, the use of an organic electrolyte allows 2.5 V to be reached, although the internal resistance of the device may be higher.

To operate at higher voltages, individual ultracapacitors are connected in series. With a string of more than three capacitors, voltage balancing circuits are required to prevent any cell from reaching over-voltage. Exhibit 6.4 shows a typical arrangement.

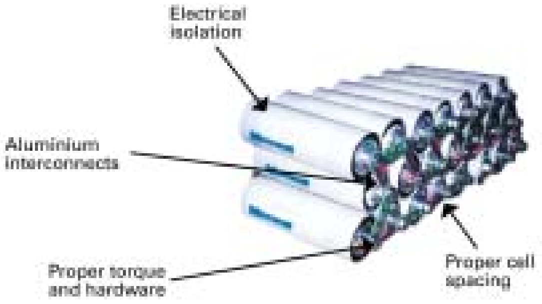


Exhibit 6.4 Maxwell Technologies ultracapacitor array with cell balancing

The amount of energy a conventional capacitor can hold is measured in micro-, nano- or picofarads (µF, nF, pF). Individual ultracapacitors by contrast have capacitances of tens, hundreds, or thousands of farads. Maxwell Technologies produces ultracapacitors in 4, 10, 100, 450, 900, 1,800 and 2,600 F sizes, which can be combined into power modules for higher voltage. The largest device at present is the BCAP0010 ultracapacitor, rated at 2,600 F.

The gravimetric energy density of an ultracapacitor is from 1 to 10 Wh/kg. This energy density is high in comparison to that of a conventional capacitor, but is only around 10% of that of an Ni-MH battery. Typical figures quoted by Maxwell Technologies during the mission were:

- Power density ≤9,000 W/kg
- Energy density ≤6 Wh/kg

Whereas an electrochemical battery delivers a fairly steady voltage until nearing full discharge, the voltage appearing across the terminals of an ultracapacitor drops linearly from full voltage to zero. Because of this, an ultracapacitor is normally unable to deliver its full charge, and this has to be considered in any design incorporating such a device.

For example, suppose a nominal 6 V power supply is required to drive a circuit that will malfunction if its supply drops below 4.5 V, a 6 V battery will only reach 4.5 V after most of the stored energy it contains has been extracted. However, an ultracapacitor charged to 6 V reaches 4.5 V within the first quarter of the discharge cycle. The remaining energy is then within an unusable voltage range.

A DC-to-DC converter could correct this

problem, but such a regulator would add cost and introduce a 10-15% efficiency loss.

Rather than operate as a main battery, ultracapacitors are more commonly used to ‘bridge’ short power interruptions. Another application is improving the current handling of a battery. The ultracapacitor is placed in parallel to the battery terminal and provides current boost on high-load demands. Ultracapacitors should also find a ready market for use with fuel cells, to enhance peak-load performance. Because of their ability to rapidly charge, large ultracapacitors have been used for regenerative braking on vehicles (see Section 9.2.3).

The charge-time of an ultracapacitor is about 10 s. The ability to absorb energy is, to a large extent, limited by the size of the charger. The charge characteristics are similar to those of an electrochemical battery. The initial charge is very rapid; topping charge takes extra time. Provision must be made to limit the current when charging an empty ultracapacitor.

In terms of charging method, the ultracapacitor resembles an LA battery. Full charge occurs when a set voltage limit is reached. Unlike the electrochemical battery, the ultracapacitor does not require a full-charge detection circuit. Ultracapacitors take as much energy as needed. When full, they stop accepting charge. There is therefore no danger of overcharge or 'memory'.

The ultracapacitor can be recharged and discharged a virtually unlimited number of times. Unlike the electrochemical battery, there is very little wear and tear induced by cycling, and age does not greatly affect an ultracapacitor. In normal use, an ultracapacitor is said to deteriorate to about 80% of its initial capacity after around 10 years. The lifetime of a typical ultracapacitor was stated by Maxwell Technologies to be of the order of 20 years.

6.1.2 Self-discharge

The self-discharge of an ultracapacitor is substantially higher than that of an electrochemical battery. Ultracapacitors with an organic electrolyte are affected the most. In 30 to 40 days, the capacity decreases from full charge to 50%. In comparison, a nickel-based battery discharges about 10% during that time. Thus, as noted earlier, ultracapacitors are best employed for short-term power storage applications.

6.1.3 Safety

Ultracapacitors have to be incorporated into a design with some caution, since they can burst (like an electrolytic capacitor) if abused. Since the electrolyte is flammable, the consequences of such a burst could be serious.

6.1.4 Future development

The goals for future ultracapacitor performance improvement are:

- Longer lifetime
- Increased rated voltage
- Wider operating temperature range
- Increased energy density
- Increased power density

Maxwell Technologies intends to increase rated voltage by up to 3 V within the next few years. An increase in capacitance by up to 50% while still using the conventional double-layer approach is also thought to be possible. For automotive applications, an operating temperature range from –35 to +105°C would be advantageous, and a primary focus for research is the development of new electrolytes based on the combination of novel organic solvents and improved conduction salts, permitting not only a higher rated voltage and a higher conductivity but also a larger operating temperature range.

The expected outcome from Maxwell Technologies' R&D effort is an increased electrolyte decomposition voltage and ionic conductance, increased electrode accessible surface, better chemical and mechanical stability, as well as improved electronic conductance, separator electronic insulation level, and ionic conductance.

During the mission's visit to MIT, the team received a presentation on carbon nanotube-enhanced ultracapacitors. The use of carbon nanotubes was stated to be 'likely to lead to a paradigm shift in ultracapacitor performance, bringing their performance close to that of a battery'. Whether this claim is true or not, it is certainly the case that current production techniques used for ultracapacitors use macro-scale processes, and there does seem to be considerable scope for enhancing ultracapacitor performance through nanotechnology.

6.2 Advantages and disadvantages of ultracapacitors for ES

Advantages

- **Virtually unlimited cycle-life** – can be cycled millions of times
- **Low impedance** – enhances load handling when put in parallel with a battery
- **Rapid charging** – ultracapacitors charge in seconds
- **Simple charge methods** – no full-charge detection is needed; no danger of overcharge

Limitations

- **Linear discharge voltage** – prevents use of the full energy spectrum
- **Low energy density** – typically holds one-fifth to one-tenth the energy of an electrochemical battery
- **Cells have low voltages** – serial connections are needed to obtain higher voltages; voltage balancing is required if more than three capacitors are connected in series
- **High self-discharge** – the rate is considerably higher than that of an electrochemical battery

7 LARGE STATIONARY APPLICATIONS

The overwhelming majority of stationary battery systems in the USA serve as emergency backup to ensure critical loads are supported in the event of unexpected loss of mains supplies. The same pattern has applied in all other developed nations for the past 100 years.

During the past few years, however, a small but growing acceptance of other purposes for ES has been established. At present, this movement is concentrated in a fairly small but influential group of organisations and companies, most of which are represented in the Electricity Storage Association – ESA (see Section 13.2.1).

The driving force for the development of these applications is the recognition that the future sources of electrical energy and the way it is distributed will be fundamentally different from the past century. The state authorities in certain areas such as California seem to have recognised this earlier than others and are encouraging the feasibility studies and demonstration programmes that will enable the establishment of new infrastructure. At other levels, the economic incentives, such as carbon levies applied in Europe, are not being implemented, and this is hampering the general movement towards such technology at present.

Application	Composite $/kW	Hours of storage	10-year storage market (GW)	10-year storage market ($ m)
Energy arbitrage	435	4	10	5,000
T&D deferral	399	2	2.5	1,250
Energy arbitrage and deferral	834	4	2.5	1,250
Transmission constraints	625	6	0.8	400
Time of use rates	592	6	3.3	1,700
Demand charge management	40	6	3.3	1,700
Microgrid	391	6	1	500
Renewables capacity firming	100	6	0.1	50
Renewables time shifting	396	6	0.2	100

Exhibit 7.1 Applications and markets for stationary ES (source: CEC PIER market analysis, 2003)

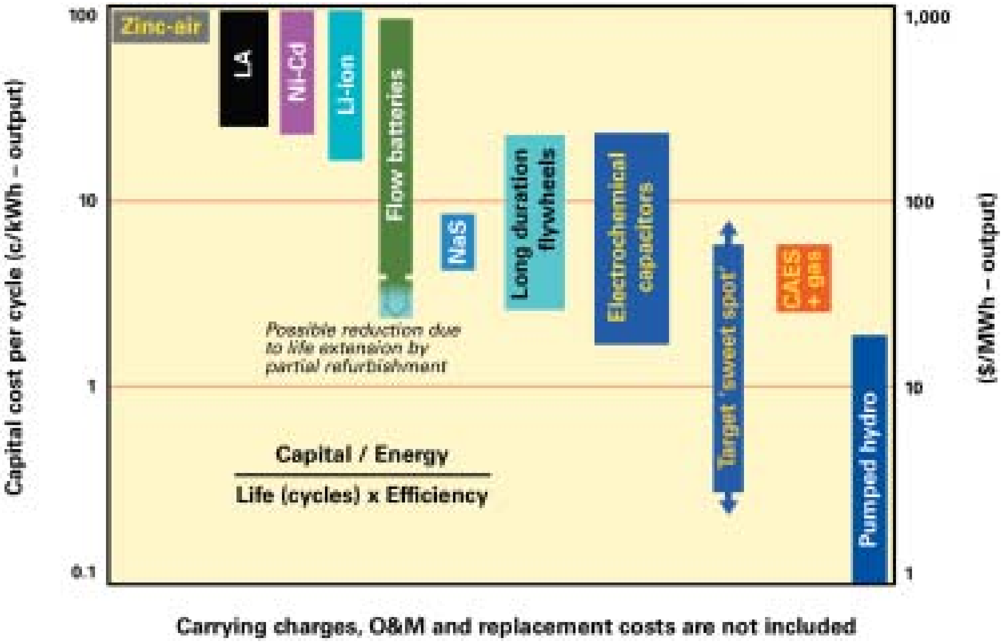


Exhibit 7.2 Per-cycle cost of ES systems for frequent charge/discharge applications (source: CEC)

Examples of some of the potential applications of stationary ES and their US market size are given in Exhibit 7.1.

The performance requirements of these applications are diverse, particularly in respect to the power, discharge period and number of charge and discharge cycles experienced through the life of a storage system. As a result, it is highly unlikely that a single ES system will emerge that will provide the best solution to all applications.

The apparently confusing array of options for ES that are being developed at present may be part of the cause for a slow uptake in commercial activity. It is a significant opportunity for companies with the range of expertise to make impartial and objective assessments of individual customers' requirements. In several of the subsequent examples, this system-integrator role has been played by European companies, and the opportunities should be considered carefully by UK engineering groups.

7.1 Puerto Rico Electric Power Authority (PREPA) battery energy storage system (BESS) (Sabana Llana, PR)

This system was constructed in the early 1990s and was the world's largest battery energy storage system (BESS) until the Golden Valley system in Alaska was opened in 2003 (see Section 7.3). The purpose of the system was to provide spinning reserve and frequency control for the relatively small (4,400 MW) but intensively used grid on the island of Puerto Rico (PR).

Exhibit 7.3 PREPA's BESS facility, Sabana Llana, PR (source: PREPA)

Exhibit 7.4 LA battery rack at PREPA's Sabana Llana BESS (source: PREPA)

The system was rated for 21 MW_{ac} power output and a storage capacity of 14 $MW_{ac}h$. It was designed to provide 20 MW_{ac} for 15 minutes plus a 15-minute ramp-down to zero MW_{ac} for spinning reserve. It was designed to do this an average of 55 times per year, and would be recharged at off-peak times overnight. The system could also inject or absorb 10 MW_{ac} instantaneously for continuous frequency control.

The Sabana Llana BESS consisted of 6,000 flooded LA cells supplied by C&C Batteries Inc. The cells were of a flat-plate design using lead-calcium alloy grids in both positive and negative plates. The cells were arranged in six parallel strings of 1,000 cells each, to provide a nominal bus voltage of 2,000 V_{dc}. The system included cell electrolyte agitation with compressed air, and an automated cell watering system.

The power conversion system (PCS) was a 20 MVA_{ac} bi-directional 18-pulse, stepped-wave GTO thyristor-based voltage source converter, supplied by General Electric. The battery input voltage was 2,000 V_{dc} and the AC line voltage was 13.2 kV_{ac}. The engineering, installation and overall system integration was performed by United Engineers and Constructors.

The BESS was completed in 1994 and its first major event was in November of that year when a 410 MW_{ac} steam plant failed, resulting in a 21% system overload. While load-shedding could not be avoided, the effects were mitigated by an 80 MW_{ac} contribution from the BESS. In 1998 another major success was the support of the only remaining transmission line to the north-eastern part of the island in the aftermath of Hurricane Georges.

Less dramatic benefits are obtained on a daily basis, however, and these are considered to be equally significant to the power engineers who explained the operation of the plant to the mission. The first effect is regulation of frequency across the grid. This is maintained within a range from 60.4 to 59.6 Hz, and energy is supplied or absorbed by the battery if the rate of change in frequency is greater than 0.25 Hz per second. By using the BESS rather than conventional control methods, the stress on power conversion and generation equipment is significantly reduced, leading to savings in maintenance costs and downtime.

The other major benefit is to provide rapid response to the changes in demand which occur during each day. PR's climate makes air conditioning a virtual necessity in most homes, but because of the lower standard of living compared with the USA, for example, many households cannot afford to run air conditioners continuously. This results in large surges in demand each evening as people arrive home from work. The BESS can provide short-term support while the main generating plant output is increased more slowly. This allows the plant to be run at lower output levels, consuming less oil, during periods outside peak demand, in the knowledge that sudden demand fluctuation of seconds or minute timescales will not result in serious grid instability.

The only significant drawback to the BESS operation was in fact the service-life of the originally-installed cells. The first cell failures were noted in 1995, less than one year after commissioning. The failure mode was active material shedding causing loss of capacity in approximately 50 cells. A programme of individual cell replacement was initiated that continued through the life of the original system, until it was closed for complete replacement after the expected lifetime of five years, in 1999. During this period, the average life of cells was ~3.5 years, but with large spreads between individual cells.

This situation resulted in litigation with the battery suppliers, who blamed the control system for the short life. A decision was made by PREPA not to use flat-plate cells in future but to insist on flooded tubular-plates for a replacement system. These cells have lead-antimony alloy positive grids, and the active material is tightly held by woven gauntlets to prevent shedding. These cells have shown their value in PV applications, where many charge-discharge cycles of varying depth are experienced. By contrast, the flat-plate flooded cells supplied by C&C Batteries are successfully used in traditional stand-by applications where cycling is minimal.

Since 1999, the BESS has experienced a long hiatus caused by the high import tariffs on batteries engendered by the so called ‘banana wars’. A first round of tendering in 2000 was abandoned, and the plant was mothballed until new batteries could be purchased in 2004. These are tubular-plate cells manufactured in Brazil.

The same layout of 6,000 cells has been maintained but the compressed-air circulation system was not considered necessary, and a semi-automatic watering system is employed. The battery installation was complete at the time of the mission visit in November 2004, but refurbishment work was still necessary on the PCS.

PREPA estimates the cost savings yielded from the BESS to be ~$1 million/year; this is expected to pay back the $1.5 million replacement cost of the battery system in under two years. Even with the shorter than expected life of the original batteries, it has enabled the site to attract the funding necessary to update the battery system, in the face of many other demands for resources within the company.

7.2 Substation UPS (STMicroelectronics, Phoenix, AZ)

This system was installed to provide uninterruptible power supply (UPS) to a high-volume semiconductor wafer fabrication plant. Analysis of short-duration supply variations in the medium-voltage distribution from a local substation showed 12 incidents of voltage dips of up to 50% and one of greater than 50% of normal supply. The duration of these dips was several seconds at most, but this was enough to lose control of critical processes that required much longer periods to be reinstated.

Three alternative solutions were considered to improve the reliability of the plant:

1. Conventional low-voltage UPS distributed throughout the facility to protect the most critical equipment only (~4 MVA)
2. Solid-state source transfer switch (STS) between two utility feeders at 12.47 kV
3. Medium-voltage UPS (12.5 MVA at 12.47 kV) to protect the entire operation

Analysis of the 13 incidents observed prior to installation indicated that only the third option would have provided full protection to plant. This option was also selected because it could be installed with the least disruption to the operation of the plant.

Because of the short discharge duration required, the UPS supplier chose SLI batteries normally applied for diesel truck starting,

Exhibit 7.5 UPS module at STMicroelectronics, Phoenix, AZ (source: ESA/S&C PureWave)

supplied by Delco. These are LA batteries with thin-plate construction optimised for higher current outputs than typical stationary batteries. Normally, such batteries would have very short life in a UPS application, where they are continuously connected to a charging supply, which results in corrosion of the thin positive grid wires.

The S&C PureWave UPS modules minimise this problem by disconnecting the battery until it is required to support the load or for periodic charges to replace self-discharge losses. To further protect the batteries, the whole system is housed in air-conditioned containers adjacent to the substation supplying the plant.

This system has been in operation since August 2000. It has been highly successful in mitigating an average of 20 incidents per year, providing payback time of around two years for this installation.

The stability of the batteries, in this and previous smaller applications, has been studied by DOE's SNL (see Section 12.13).

A five-year life has been established, with impressive mean time between failure (MTBF) statistics.

Given the very small energy throughput that this system experiences, it is probably not valid to call it a BESS. Some of the benefits of the controlled temperature and charging environment could be beneficial for battery types that are able to sustain deeper and more-frequent discharges but this has not been demonstrated yet. The use of flat-plate, especially SLI-type batteries, would not be acceptable in BESS applications, as illustrated by the PREPA experience.

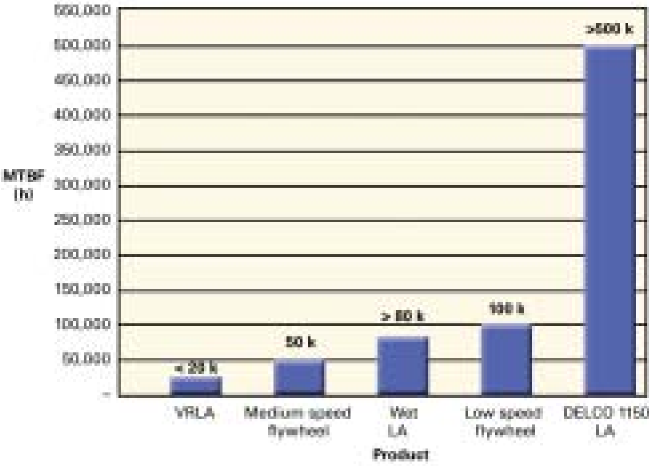
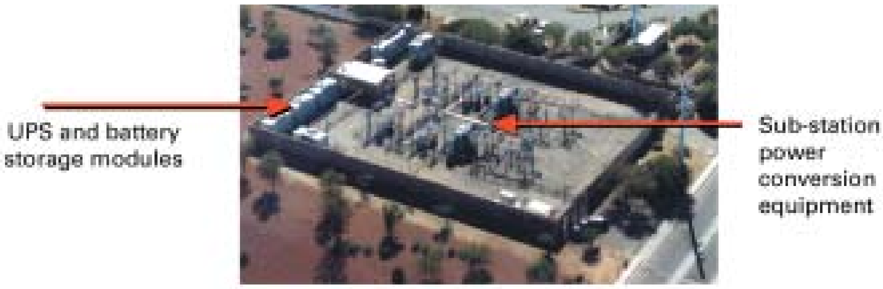


Exhibit 7.7 ES technology performance comparison for STMicroelectronics (source: SNL)

This example does illustrate the importance of matching the optimum technology to a particular application, and the degree to which existing battery products can be adapted by incorporating new control technology.

The duration of the discharges required from this UPS indicate that it is in the range currently targeted by ultracapacitors and flywheel

Exhibit 7.6 ES facility at STMicroelectronics, Phoenix, AZ (source: ESA/S&C PureWave)



systems. The cost of these systems has decreased significantly over the last ten years but still has some way to go before reaching LA levels. If these new technologies have to compete against the most competitively priced segment of the LA market, which still have replacement periods of five years or more, it could defer their viability in medium to large systems for many years.

7.3 Golden Valley Energy Authority (GVEA) BESS (Fairbanks, AK)

Exhibit 7.8 Ni-Cd battery rack at GVEA's Fairbanks BESS (source: ESA/Saft)

This system has taken the title of world's largest BESS from the Sabana Llana site in PR (see Section 7.1). The purpose of the plant is to reduce the dependence of the town of Fairbanks in central Alaska on locally-generated electric power. The local power generators are oil-fired, requiring costly tanker shipments for supply. As much power as possible is supplied from coal-fired power plants based on the coast in Anchorage.

When disturbances occurred to the coastal generation plants or the high-voltage transmission system, this resulted in load-shedding until local generators could increase their output. Analysis in the mid-1990s indicated that 70% of the load-shedding incidents could be avoided by the presence of 40 MW of stand-by power which was instantly available. Autonomy of up to 15 minutes was required to cover these incidents.

An Ni-Cd-based BESS was selected by GVEA to meet this requirement. ABB acted as the engineer and system integrator, and the cells were supplied by Saft. The system was installed in two stages, with the second stage going online in December 2003.
The key system parameters are:

Power conversion system:

- 40 MVA rating, 46 MVA maximum output
- 2 modules applied of 20 MVA each
- Water-cooled IGCT-based power circuits
- AC grid voltage 138 kV
- DC link to batteries operates up to 5,200 V/12,000 A

Battery system:

- Ni-Cd pocket-plate cells
- 3,440 x Saft SBH 920-Ah cells connected per series string
- strings connected in parallel
- 10-cell modules mounted in industrial pallet rack system
- Output capability 40 MW for 7 minutes, or 26 MW for 15 minutes (nominal rating)

Exhibit 7.9 10-cell Ni-Cd battery module at GVEA's Fairbanks BESS (source: ESA/Saft)

During 2004 the system mitigated 56 power outages, providing average discharge durations of 9-10 minutes. These have all been achieved successfully, with no reports of cell failures.

The overall installation budget was $40 million, and estimated battery lifetimes of 20 to 30 years should enable the whole lifetime costs to be competitive with other technologies. The cost of power failures before the system was installed was estimated at $7 million per year, so a payback of around 6-7 years is anticipated.

Saft has committed to support the project through end-of-life of the batteries, which will need specialist deconstruction and recycling operations to meet environmental concerns.

The system represents the first major showcase for the use of Ni-Cd on this scale, and is being closely monitored by US power and environmental agencies. EPRI (see Section 13.2.2) and SNL (see Section 12.1.3) have taken an active role in supporting the development of this system and will be responsible for producing independent assessments of the effectiveness of the system throughout its life.

7.4 American Electric Power BESS evaluation site (Gahanna, OH)

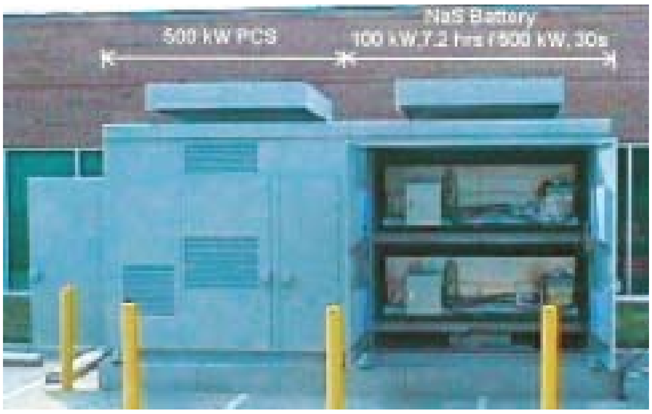


Exhibit 7.10 Na-S BESS supplying AEP offices in Ohio (source: ESA/NGK)

Although sodium-sulphur (Na-S) battery technology has been under development for almost 40 years, and originally was expected to meet the requirements of EV applications, at the current time no indigenous US battery manufacturers are producing Na-S batteries: following a number of safety problems with early commercial batteries, work has stopped in almost all areas. The exception has been NGK Insulators Ltd of Japan, which has more than 20 years of development experience and has concentrated for most of that time on large stationary batteries for load-levelling applications.

Most of the commercial systems produced by NGK are based in Japan, but the first system in the USA has been bought by American Electric Power (AEP) for evaluation purposes. The partners in this evaluation project are AEP, NGK, Tokyo Electric Power Co (TEPCO), ABB, SNL and EPRI.

The Na-S battery system is built from modular cell groups to provide flexibility of power and ES in each application. The basic characteristics of the cell modules are shown in Exhibit 7.11.

Pulse power	250 kW (30 s)
Rated power	50 kW
Energy	360 kW
Dimensions	2,200 W x 1,762 D x 640 H (mm)
Weight	3,600 kg

Exhibit 7.11 NGK Na-S battery module and specification (source: ESA/NGK)

Two of these modules are installed in the Gahanna BESS. The system has been operational since September 2002 and serves two main purposes: to provide short-term power-quality stability and to provide peak energy-demand shaving. The power-quality function has worked successfully for all events experienced since installation. These occur approximately once per month.

The peak-shaving function is utilised on a daily basis, and three main regimes have been applied with discharges, as shown in Exhibit 7.12.

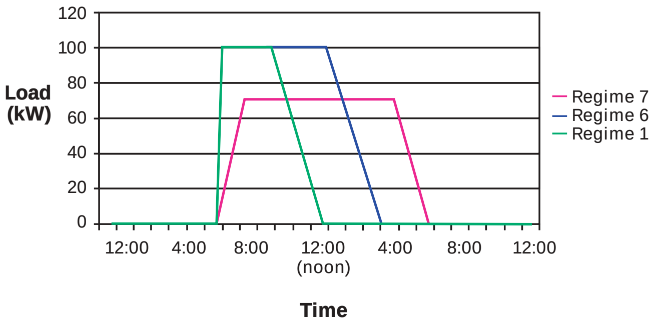


Exhibit 7.12 Operational regimes at the Gahanna BESS

The energy efficiency for each of these conversion profiles has been calculated during the period of operation. For each regime, a value of ~91% was achieved.

The listed price for each module is currently $85,000-95,000 (~£45,000-50,000) in the USA depending on factors such as number of modules, power configuration, location, etc. This is projected to reduce to $75,000 (~£39,000) in 2006 when the next scale-up in NGK production facilities is completed, and to reach a mature price level of ~$55,000 (~£29,000) per module. In 2004, manufacturing capability was close to 150 modules per year. This is being expanded to 400 per year by 2006.

The projected cycle-life based on completed laboratory tests is 4,500 cycles to 90% DOD. This indicates a life of 15 years in load-levelling applications. The profitability of this application depends critically on the variation in electricity tariff levels through a daily cycle and at different loadings. Where these values are subject to significant change through the life of the battery, it adds to the risk of the initial investment. If dual functionality can be considered, such as UPS or power-quality benefits, then the financial effects are much more readily assessed.

The main promoter of this system is TEPCO in Japan, but the commercialisation is being followed very carefully by energy suppliers in the USA.

7.5 Zinc-bromine flow cell BESS for deferral of T&D upgrade (San Francisco, CA)

This system is one of three projects partly funded by CEC (see Section 12.5.1) to evaluate the contributions ES systems can make to the requirements of California's energy supply network. The other systems are based on flywheel and ultracapacitor technology.

Zinc-bromine (Zn-Br) batteries have almost as long a history as LA batteries, but have never gained wide acceptance due to difficulties with the long-term stability of both electrodes. Development activity increased in the 1970s and 80s when it was considered to be viable for EV applications. This has not come to fruition, and only one company (ZBB, based in Australia) is currently active in development of this electrochemistry. Now the emphasis is on large-scale ES where the relatively high energy density and ready availability of the raw materials are attractive features.

The problems associated with electrode stability in conventional battery architectures have been largely mitigated by the use of a ‘flow cell’ design, where the active materials are stored in separate tanks and only pass into the electrode compartment during charging or discharging events.

The Zn-Br flow cell (Exhibit 7.13) differs from other flow cells because the zinc metal produced during the charging process remains in the cell, deposited on the negative electrode surface. During discharge, this zinc dissolves and is then free to move to the storage reservoir.

ZBB have concentrated their design on a modular system of a size that can be containerised and moved easily to the point of use. This flexibility is a feature that is key to their route to market. In the San Francisco

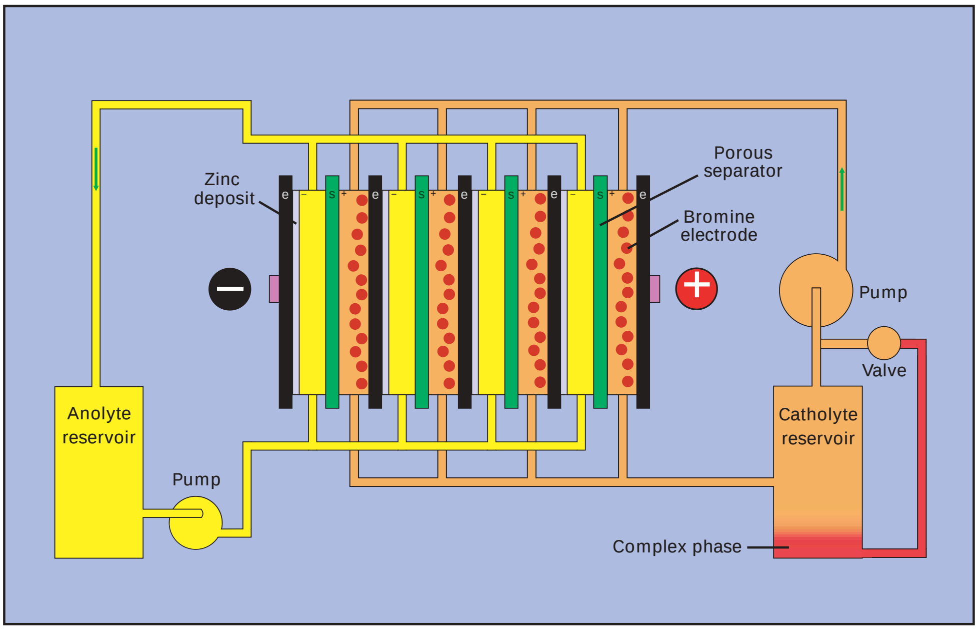


Exhibit 7.13 Zn-Br flow cell (source: ESA/ZBB)

project, the system will be used at locations where T&D assets are at the limits of their capability, and where future expansion is not clearly viable. In such cases, the flow cell system can cover peak loads while alternative power supplies are developed if necessary.

Exhibit 7.14 500 kWh transportable Zn-Br BESS (source: ESA/ZBB)

The San Francisco project will supply four modules with a total capacity of 2 MW output and 2 MWh capacity to a substation owned by Pacific Gas and Electric Co (PG&E). The total system cost is $2.5 million (~£1.3 million) of which the CEC-DOE Collaboration on Energy Storage (see Section 12.5.1) is contributing 76%. The system is under construction at present and will be delivered in 2006.

Although not fully commercialised, other 500 kWh modules have been supplied for a price of ~$163,000 (~£86,000) per module. Examples are operating to support seasonal demands for corn-drying kilns and logging camps in other parts of the USA.

7.6 Vanadium ‘redox’ flow cell BESS for support of long-distance power transmission (Castle Valley, UT)

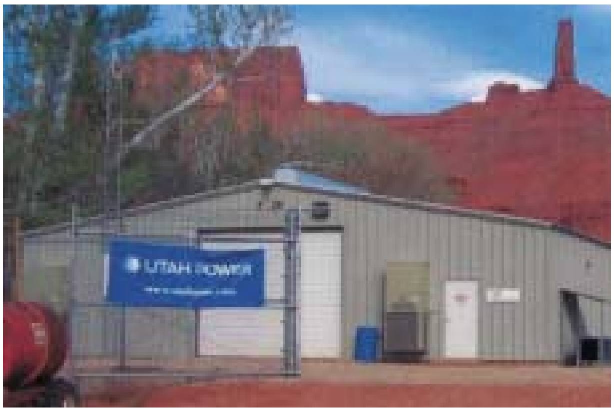


Exhibit 7.15 Vanadium redox flow cell BESS facility at Castle Valley, UT (source: ESA/VRB)

The purpose of this system is to support the supply of power across an 85-mile, 25 kV distribution feeder line. Customer power consumption is increasing to a point that peak-period loads are leading to voltage regulation problems (power factor <0.6).

Conventional solutions such as transmission line reinforcement, substation upgrade or increased reactive compensation, were considered to be less economical or environmentally acceptable than the proposed system from VRB Power Systems Inc, based in Vancouver, Canada. The BESS supplies power when the demand exceeds the limit of the transmission line for 6-7 hours each day. When demand drops below the supply limit at night, the system is recharged.

The vanadium ‘redox’ (reduction/oxidation) technology has similar characteristics to the Zn-Br flow cell system, but in this case all active materials are soluble, and consist of vanadium ions in different oxidation states dissolved in sulphuric acid solution of a similar concentration to that used in LA batteries.

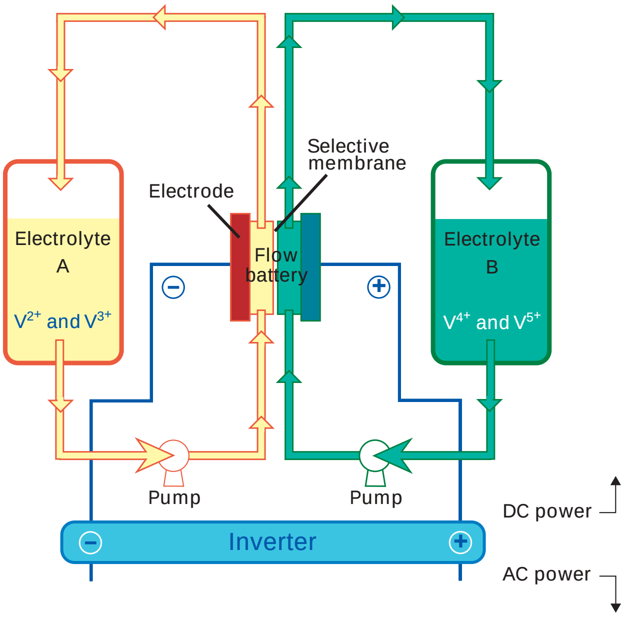


Exhibit 7.16 Vanadium redox flow cell system (source: ESA/VRB)

The flow cell has a storage capacity of 2 MWh which can be upgraded at relatively little cost by the addition of more storage space and electrolyte. The output is up to 250 kW (+/-250 kVAR for power-factor correction).

The plant is housed in a conventional light industrial unit where temperature must be controlled within 5-40°C range and provision made for extraction of hydrogen gas that can be formed during charging.

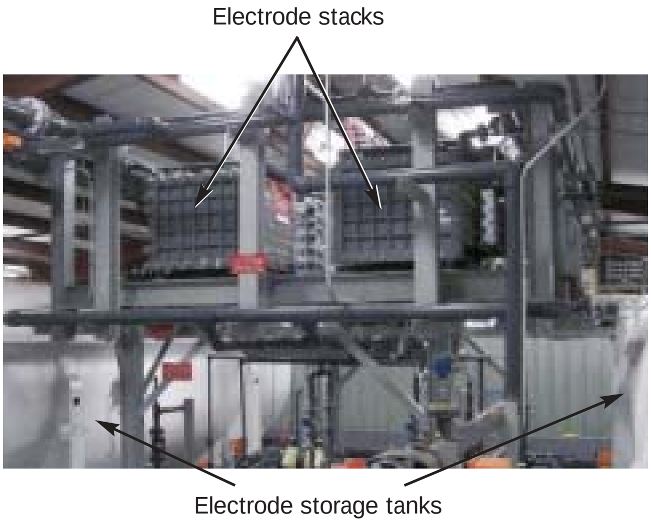


Exhibit 7.17 Vanadium redox flow cell at Castle Valley, UT (source: ESA/VRB)

The plant is designed for unattended operations, with cell-stack maintenance and ion-exchange membrane replacement every 10-15 years. The evaluation of these conditions is a key part of this programme of operational testing.

The plant has been performing full-power daily operations since March 2004 and has demonstrated stable operation. Feeder voltage deviations have improved by 2%. Monitoring will continue as consumer loads increase beyond the capacity of the existing transmission line. An additional benefit has been an improvement in power factor on the feeder line, which has reduced line losses by 40 kW. This more than recovers the losses from parasitic chemical reactions within the BESS.

Initial costs per kW are relatively high for flow cells, at ~$250,000 (~£132,000) for the 250 kW module in this example. The larger energy capacity of the system makes it more cost effective as longer load-levelling discharge times are reached, especially of 10 hours or above.

7.7 Zinc-cerium flow cell ES systems

Another flow cell system that utilises zinc as an active material is under development by Plurion Systems Inc of Reno, Nevada. The positive active material in this system is dissolved cerium, which converts between the Ce^{3+} and Ce^{4+} states during charging and discharging. The system is illustrated in Exhibit 7.18.

The Ce^{4+} species is particularly aggressive to many materials but suitable cell constructions have been developed to allow pilot-scale storage systems to be produced. The main technical advantages claimed for this system are a high operating voltage for each cell and an electrolyte that is not degraded by transfer of material across the semipermeable membrane that separates the two half cells.

Plurion has no demonstration systems in place at present and is seeking collaborators to identify load-levelling and UPS applications.

7.8 Key messages

- There is no single ES technology that clearly has the potential to dominate this market now or for the foreseeable future
- The diverse nature of ES requirements means that different technologies will be able to occupy discrete niches of the market
- The potential value of ES is recognised by relatively small but very motivated groups within the US energy industry
- The necessary economic/regulatory incentives are not yet in place to encourage the take-up of energy storage in mainstream activities
- The demonstration plants for each technology have been in rather unique situations that maximise the benefits of the BESS. This does not necessarily demonstrate the relevance to more general usage
- A great deal of preparatory work has been done by activists in the field, such that market growth could be very rapid once a 'tipping point' is reached

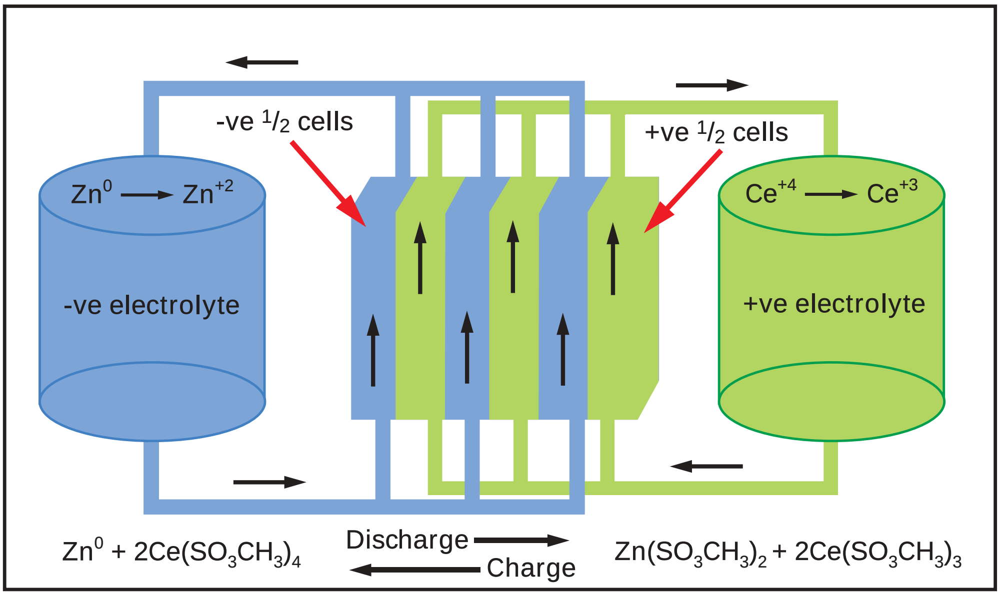


Exhibit 7.18 Zn-Ce flow cell (source: Plurion Systems Inc)

8 CRITICAL POWER APPLICATIONS IN A DISTRIBUTED ENVIRONMENT

Although electrical power is a mundane topic to the public in normal circumstances, interruptions in supply immediately bring to light how much of modern life depends upon it. Unless special measures are taken, loss of power shuts down emergency service call centres, hospitals, the supply of water, gas and oil (much of the water supply is pumped and other services are controlled by electrically-operated valves), air traffic control (ATC), street lights and traffic lights, telephone, radio and TV communication, banks, insurance, industry and the data networks that allow all of commerce to operate. For this reason, many services have their own emergency sources of power (that is why the telephone system continues to operate during power failures, for example), but these resources are used in isolation and are not available to back up the utility supply.

The ever-increasing dependence upon digital traffic, with its requirement for uninterrupted communication, exacerbates the need for security of supply.

The threat of terrorist activity, such as the '9/11' attacks in the USA, increases the need to consider resilience of the national electricity transmission and distribution (T&D) infrastructure and to avoid the type of cascading fault which occurred over much of the north eastern portion of North America in August 2003.

Fossil fuels used for electricity generation are a limited resource which cannot be regenerated in short timescales, thus must be considered as non-renewable. Emissions from fossil-fuel-powered generating plants cause pollution: they can be reduced, but not eliminated. Nuclear power provides a clean method of generation, but produces waste requiring very special treatment and storage. The potential for contamination from incorrectly handled waste or from a failure within a power plant means that nuclear-powered generation has its detractors.

In order to reduce the dependence on fossil fuels without resorting to nuclear power, governments worldwide are supporting initiatives to increase generation from renewable energy (RE) sources such as hydroelectric power, wind farms, solar photovoltaic (PV) installations, wave and tidal energy, geothermal generators, and investing in future technology such as that associated with a 'hydrogen economy' (eg fuel cells).

In order to gain the most benefit from RE sources whilst at the same time improving the reliability and efficiency of the electrical mains supply grid, the storage of electrical energy and the concept of 'microgrid' networks which incorporate users' emergency backup installations is seen as an economic way forward that offers improved reliability and energy efficiency. This concept is in actual use in the State of California and is recognised by many US government agencies as the future of an integrated public mains supply network.

This chapter reports on the issues and the progress being made across the USA as agencies plan and install ES solutions as a means of stabilising electricity grid networks and maximising the benefits from a range of RE sources.

8.1 Critical applications

The infrastructure of the economy of all but the poorest Third-World countries is increasingly dependent upon reliable provision of electricity supplies. Interruptions in the supply disrupt many services and networks that are considered critical in modern society and, as a result, such services increasingly maintain an uninterruptible power supply (UPS).

Telephone exchanges operate from DC backed up by large batteries, and the AC supply is also backed up by diesel generators. Banks, insurance companies and ATC use UPS to ensure that there is no loss of power – the UPS converts the utility AC supply to DC, where it is backed-up by a battery, then back to AC.

Data systems are particularly sensitive to AC interruptions: whereas a heating system or furnace may be unaffected by a loss of power of several minutes, computer systems are unable to operate without power for more than one hundredth of a second. Even interruptions which hardly cause lights to flicker can cause a computer to crash.

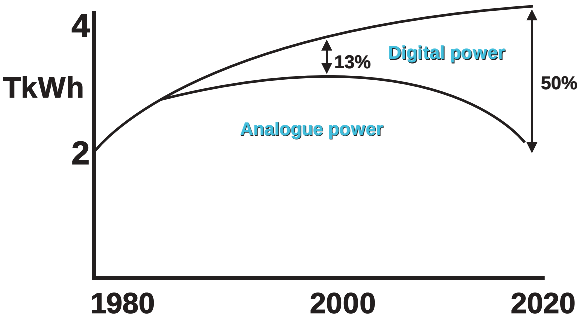


Exhibit 8.1 Increasing demand for high-quality power for digital loads

Exhibit 8.1 shows how the proportion of power consumed by digital loads in the USA is expected to rise over the next fifteen years, placing ever more burden on the quality of the utility supply.

In recent years, major power outages have occurred in the USA, Canada, Europe and elsewhere. The threat of a power outage has increased considerably due to a measured and perceived increase in adverse weather incidents (possibly an effect of climate change) and the increase in domestic and international terrorist activity. There are other contributing factors in any outage, and these range from increasing load, underinvestment in equipment, technology and/or capacity, plus insufficient maintenance. The end result of loss of utility power endangers life and damages the economy.

8.2 Vulnerable public grids

Across North America and Europe, concerns are being raised on the reliability and vulnerability of utility power distribution networks across nations and continents. Recent outages and threats have raised awareness on both sides of the Atlantic, and in particular in the USA, where actual outages have necessitated that formal reports and recommendations be produced.

Various government departments and agencies, including the DOE, the North American Electric Reliability Council (NERC), EPRI and the Federal Emergency Management Agency (FEMA), amongst many others, have added a voice. The technical conclusions and recommendations have one common theme: the network is critical to today's way of life, and actions have to be taken to reduce the wholesale risk of local, regional or national failure.

Some examples of large-scale outages and their causes are:

- September 2003, Italy/Switzerland – domino effect from single line failure
- September 2003, Demark and Sweden – switching failure domino effect
- August 2003, South London – heat-related National Grid failure
- August 2003, North-eastern USA and Canada – heat/load related
- September 2001, New York City – two main substations destroyed by Twin Towers collapse
- July 1999, New York City – heat/load failure
- December 1998, San Francisco – working party failure
- Winter 1998, North-eastern USA and Canada – ice storms bring down power grids
- October 1997, San Francisco – malicious disconnection
- August 1996, West Coast USA – transmission line failure causes rolling blackouts
- April 1992, Chicago – flooding shuts down utility in city centre for several weeks
- May 1986, New York City – switching failure
- July 1977, New York City – lightning strike
- November 1965, Ontario, Canada – fault causes 18-hour blackout in North-eastern USA

As a direct result of the 9/11 attacks, a US Executive Order was issued one month after, stating:

'The information technology revolution has changed the way business is transacted, government operates, and national defence is conducted. Those three functions now depend on an interdependent network of critical information infrastructures. The protection programme authorised by this order shall consist of continuous efforts to secure information systems for critical infrastructure, including emergency preparedness communications, and the physical assets that support such systems. Protection of these systems is essential to the telecommunications, energy, financial services, manufacturing, water, transportation, healthcare, and emergency services sectors.'

A necessary business risk assessment should always consider the consequences of a power outage, and as a result many businesses are purchasing UPS with battery backup and diesel generating plant. As a result, latest US figures suggest that somewhere in the order of 25 GW of large UPS stand-by equipment exists within business and government buildings, with a further 10-15 GW of smaller desktop-size units in business and home-office use.

Individual companies take this matter very seriously: for example, AOL facilities in Virginia have 13 x 2 MW diesel generators, while telecom operators throughout the world have become major owners of distributed generation and ES capacity.

The point is that sustainability in a digital economy requires total power availability, but what is recognised in the USA is that the solution may be to pool efforts and investments, and to link the resources of the national T&D infrastructure to the substantial emergency power equipment at a local level. This concept may have more bureaucratic barriers than technological issues to resolve, but an integrated grid network could have economic benefits for power generating and distributing utilities and end users who benefit from reliable backup, and can offset investment in some way by economically storing energy from RE sources.

As a result, companies such as BT are actively investing in combining RE power generation with stand-by ES systems, and leveraging the economic and social benefits that can be gained from using sustainable resources to power its new 21st Century Internet Protocol (IP) networks.

However, it is also clear from a number of statements made in the USA (also relevant in the UK) that much more could be achieved with increased investment in ES technologies that can then unlock the triple-play benefits of reliable, renewable and economically profitable local energy generation and storage.

In order to ensure that sensitive loads are not interrupted, it is essential to provide local backup (however good the utility supply is, builders can still dig through cables), so users of critical equipment such as those listed above and the military will continue to have their own backup power systems. For the sake of the economy, more use should be made of these facilities for local power storage, load-levelling, and other needs.

8.3 Sources of electrical energy

8.3.1 Available technologies

Electricity generation in the USA is predominantly based on fossil fuels, with 50.1% of the 3.86 TWh generated in 2002 coming from coal, 17.9% from natural gas and 2.5% from oil. Nuclear generation accounts for 20.2%, while 6.6% is hydro power and 2.3% from other RE sources such as wind power (1.8 GW of wind turbines are currently installed in the USA), solar PV and biomass.

If cars move to fuel-cell powered drivetrains, they may also provide a source of stand-by power once the ‘hydrogen economy’ is established: one million vehicles, each with a 10 kW generator, provides an emergency source of 10 GW. The peak demand in the average HEV is ~18 kW.

8.3.2 Effect on resources

The availability of most sources of RE is intermittent (wind, wave and solar energies are not always present; even tidal energy falls to zero at high and low tides). The use of RE sources such as via wind farms thus reduces the total consumption of fossil fuels and the associated emissions, but it does not reduce the total capacity of fossil-fuelled power stations, as the same amount of total capacity must be available whether or not the wind is blowing or the sun is shining.

Because the time taken to provide power from a cold-start of a conventional power station is far greater than the warning of impending loss of output from RE sources, and in order to allow for unpredicted load increases, more generating plant must be kept active than required to supply the immediate load demand (‘spinning reserve’). Use of local diesel and turbine generators, which are capable of faster start-up than conventional power stations, can reduce but not eliminate the need for spinning reserve.

Owing to the intermittent nature of RE sources, grid instability has been shown to occur when the proportion of total energy consumption provided by RE sources exceeds a level of between 5% and 15%. This phenomenon was observed several years ago in Denmark, and performance of all items connected to the Danish grid is closely specified to ensure compatibility.

A report[7] by the US DOE’s National Renewable Energy Laboratory (NREL) gives detailed background data on the effects of RE sources on grid infrastructure and stability.

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[7] *Report on Distributed Generation Penetration Study*, NREL/SR-56-34715, August 2003

The UK government has set a target of 10% of electrical energy consumed to be provided by RE sources by 2010, and, despite disagreements over the value of the Kyoto Protocol, the State of California is mandated to achieve a 20% renewable electricity generation by 2017.

Since the energy crisis in California that caused rolling blackouts across the State, all power and energy policies have been reviewed, and, as a result, California has some of the most progressive RE generation and storage projects in the world, funded by the State authorities and the DOE either separately or through joint programmes (see Section 12.5.1).

In Europe, 2005 saw the introduction of the European Trading Scheme, and, in anticipation of this new carbon emissions marketplace, BT placed the world's largest 'green energy' contract whereby all of BT's electrical energy (whose total energy consumption for 2004 was 2,100 TWh) will in effect be generated by environmentally-friendly sources for the next three years. Supported at all levels, this action is seen as a major change in the marketplace that immediately moves RE generation from a niche to a mainstream market commodity that will add further impetus to the generation of electricity from RE sources, and this in turn to the benefit of ES.

UK government funding is available for generation of electrical energy from RE sources, and grants are available from various sources, including the Carbon Trust, to fund innovation. However, this has not gone far enough to assist in the integration of emergency stand-by power and storage of RE.

In the USA, considerable funds are available for various energy initiatives but the direction of the funding is directly controlled by decision makers in Congress/government, and this can influence which product or company is involved in the initiative, and the assigned priority. Political lobbying is an essential part of this process, and political change can change priorities. A more detailed analysis of federal and state support for EES is presented in Chapter 12.

All DOE strategically agreed funding in the areas of stationary ES and 'distributed energy resources' (DER) is dispersed via Sandia National Laboratories (SNL), with the emphasis on state and industry participation. Therefore there is a centrally agreed direction from the DOE with a preference on 'demonstration' type projects delivered by public-private partnership. Examples of this in action can be seen under the California Energy Commission (CEC)–DOE Collaboration on Energy Storage, described in Section 12.5.1, that has the objective of assessing the suitability of ES in California, and also the DOE–New York State Energy Research and Development Authority (NYSERDA) Storage Initiative (see Section 12.5.2).

However, the entire federal and state funding for ES is dwarfed by the 2003 Presidential initiative to reduce America's dependence on imported oil for transportation. This initiative – the President's Hydrogen Fuel Initiative – has a budget of $1.7 billion (~£0.9 billion) over a five-year period. Although the primary driver is to substitute domestically produced transportation 'fuel' for foreign oil supplies, the implications for clean fuel and ES are clear. However, the benefits of such a 'hydrogen economy' are at least a decade away, and a combination approach may be necessary to bridge the gap: storage of electrical energy in a chemical or electrical field may provide the most effective answer.

Fuel cells and hydrogen-powered vehicles will still require an EES device in the form of an ultracapacitor or rechargeable battery. Recent predictions show that implementation of the hydrogen economy would require doubling of the world's electricity production using current methods of hydrogen production.

8.4 Options for storing electrical energy

In order to overcome the restrictions on capital and energy savings caused by the intermittent nature of RE as outlined above, it is necessary to store electrical energy. During times of excess capacity/low demand, energy may be stored using one or more of the storage technologies described in Section 1.4:

- Pumped hydro storage (PHS)
- Compressed air energy storage (CAES)
- Superconducting magnetic energy storage (SMES)
- Flywheels
- Chemical energy storage (CES – eg hydrogen)
- Electrochemical energy storage (EES)

The stored energy may then be drawn upon during times of peak demand and/or low energy availability, thus reducing the required peak capacity. This process is known as load-levelling or peak-shaving. Technologies more applicable to storing energy at utility level include PHS, CAES, SMES (although this is only at the demonstration stage) and battery energy storage system (BESS). Ultracapacitors and flywheels may be used for smaller installations and for supplying short-duration peak demands in utility systems.

Further benefits accrue from the facts that:

- Stored energy can be made available quickly, thus further reducing the need for spinning reserve
- Conventional power stations may be run at higher average loads, thus higher efficiency

Both the reduction in spinning reserve and the higher efficiency operation reduce fuel consumption and emissions.

A view commonly expressed to the mission team was that too much attention is being paid to generation in the USA, with not enough consideration (or funding) being given to storage: several organisations are now actively lobbying for more research into this area.

8.4.1 Batteries

Batteries may be used as a means of storage of electrical energy at many combinations of power and duration. The batteries are charged with off-peak power, and deliver power back to the grid via inverters when needed.

Conventional LA batteries have been used with success in types specifically designed for stationary application, and truck batteries (shorter life, but lower capital cost). High-power installations are operational in Puerto Rico and Alaska (see Sections 7.1 and 7.3 respectively).

Large-scale battery technologies (1-10 MW)

Newer electrochemical couples are also being used, including a Na-S installation rated at 6 MW, 48 MWh, at TEPCO's Obito substation in Japan.

In the USA, AEP is also testing large-scale batteries such as the similar Na-S NAS^{TM} battery in a suburb of Columbus, OH (see Section 7.4). The battery is there to provide 0.5 MW of stand-by power for 5 minutes, and is also used for up to 100 kW of peak-shaving for 7 hours per day. In this mode, the battery is charged overnight using a cheaper electricity supply tariff, and then discharges during the day, avoiding the peak electrical unit charge. This battery is supplied by NGK of Japan.

In addition, a 2 MW Zn-Br battery manufactured by ZBB Energy Corporation is in service as a supplemental power source to an overloaded substation at Menomonee, WI (see Section 7.5). The battery is on the back of a truck and can be transported wherever power is required.

A vanadium redox flow cell made by VRB is being used by Pacificorp in Utah (see Section 7.6) to support the high-voltage grid infrastructure that is at full capacity (2 MWh, 250 kW). The performance has been good so far, and payback is projected to be less than six years.

Other projects being considered for this technology are RE storage, peak load-shaving, and power quality and reliability improvement.

Medium-scale battery technologies (<1 MW)

Applications for medium-scale battery technologies range from minor utility upgrades to digital power backup such as telecom facilities. The stand-by market for telecoms is still dominated by LA technology; however, some interesting advances have been made in LMP technology at Avestor (Boucherville, QC, Canada) and in Ni-MH at Cobasys (Troy, Michigan).

- Avestor LMP battery technology (see Section 4.2.4)

There is an immediate demand for this product from applications within climatic extremes (-40°C to +65°C) and long storage times (two years without recharge) or where weight is a serious issue (106 Wh/kg). Telecoms is the primary market for this product, but LA still has the edge when it comes to price.

- Cobasys Ni-MH battery technology (see Chapter 5)

Cobasys of Detroit and Ohio (a JV between ChevronTexaco and ECD Ovonics) has also been redesigning its Ni-MH technology into modules aimed at specific markets such as telecom and utility backup and UPS. Again, the power module idea appears here with a push-pull connection arrangement to interface to the power module rack. The unit comes with onboard intelligence, and the NiGEN range is specifically targeting the distributed generation market for peak-shaving and power quality. Reliability and cyclic ability seem to be their main advantages but, again, price differences may still favour LA in a pure stand-by application.

8.4.2 Ultracapacitors

While LA battery systems are the conventional ES choice for UPS, they unfortunately cannot easily be designed to bridge short-term interruptions lasting only a few seconds.

Ultracapacitors, however, provide high power density but low energy density when compared to LA batteries; thus at high power they are an ideal ES device for maintaining DC voltage for several seconds in case of interruption. They are also suitable for providing short-duration (seconds) power surges on a local basis for such purposes as train acceleration, most of the energy being recovered during braking. The power delivery capability of a 400 V ultracapacitor UPS system at 50% load is shown in Exhibit 8.3.

Exhibit 8.2 Cobasys NiGEN rack-mounted ES substation installation

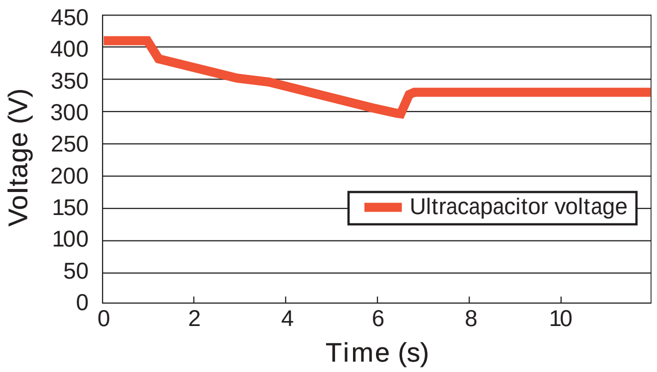

Exhibit 8.3 Ultracapacitor voltage

Further advantages such as long life, little maintenance or costly test runs, the possibility of full discharge, and short recharging times for frequent power failures, make ultracapacitors ideal for UPS applications.

Single modules rated at up to 2,700 F, 3 V are available, which may be connected in series and/or parallel to form larger storage banks. Active sharing between capacitors is needed.

Many further applications exist for ultracapacitors in hybrid systems, where short-duration pulse demands are supplied by the ultracapacitors, while longer-duration energy demands are provided by batteries, generators, etc.

8.4.3 Comparison of storage options

Exhibit 8.4 presents EPRI data that represent typical applications for each of the ES technology options. Comparisons of costs for equal time durations of ten hours show that CAES, PHS, flow batteries and hydrogen storage provide the best predicted solutions for high-level ES. The viability of CAES and PHS depends upon local geography, however.

Flywheels and ultracapacitors provide economic solutions for short-term pulse absorption.

It is clear from preceding sections that the need for ES is rising for a number of reasons – to:

- Improve the quality of the T&D infrastructure
- Prevent interruptions
- Ensure stability as the proportion of RE rises
- Improve the economics of electricity supply (load-levelling and reduction in spinning reserve)
- Many other reasons

Exhibit 8.5 illustrates a broad range of these applications of ES, relative to storage plant capacity and discharge time capability.

CAPITAL COST ESTIMATES FOR ENERGY STORAGE OPTIONS

Technology		$/kW	$/kWh	Hours	Total capital cost $/kW
CAES	Large: 100-300 MW	390	1	10	400
	Small: 10-20 MW (goal)	400	33	3	500
PHS	Conventional: 1,000 MW	1,100	10	10	1,200
	Underground: 2,000 MW (goal)	1,200	50	10	1,700
Battery	LA: 10 MW	150	250	2	650
	Advanced: 10 MW (goal)	150	150	2	450
	Flow cell: 10 MW (goal)	150	100	2	350
Flywheel	1 MW	200	300	2	800
SMES		150	300	2	750
Ultracapacitor		150	3,600	1 min	210
Hydrogen	100 MW (goal)	450	30	10	750

Exhibit 8.4 Comparative data for ES options (source: EPRI)

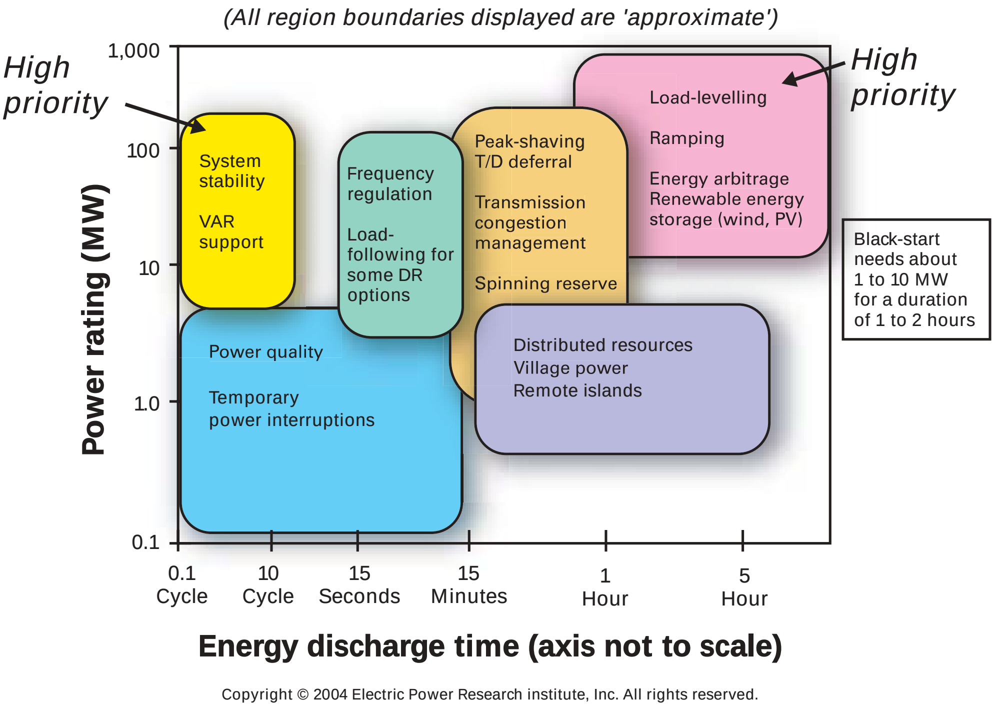

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Exhibit 8.5 Applications for ES plants within the electricity infrastructure (source: EPRI)

As a result, there are a number of ‘sweet spots’ for different ES technologies. The Electricity Storage Association (ESA, see Section 13.2.1) has considered the applicability of different storage technologies to different high-power/energy situations and attempted to identify these sweet spots (please refer back to Exhibit 1.3 in Chapter 1).

ES, with its clearly growing role as a critical enabling technology linking electricity supply to electricity demand, has an increasingly strategic dimension. This strategic importance is illustrated schematically in Exhibit 8.6.

8.5 Electricity supply and storage issues for California

Investigations into the rolling blackouts/ ’brownouts’ caused by the Californian energy crisis of 2000/2001 not only highlighted the issues brought about by deregulation of the energy supply market and the collapse of generation initiatives, but also other issues such as:

- Distribution bottlenecks (eg San Francisco)
- Underutilisation of wind power (~1.7 GW)
- Proliferation of uncontrolled direct generation
- Overall system reliability

These issues are not just confined to California, and resulting disruptions of supply could be reproduced in most regional and city-wide distribution networks. The CEC recognises that advanced ES has the potential to solve many of the State’s immediate problems, and is actively seeking technically sound, cost-effective ES technologies to provide a solution that will deliver a reliable electricity system with energy management for California.

As a result, CEC is looking at ES possibilities at generation, T&D and end-user levels. Much of the ES activity is being undertaken through the CEC-DOE Collaboration on Energy Storage;

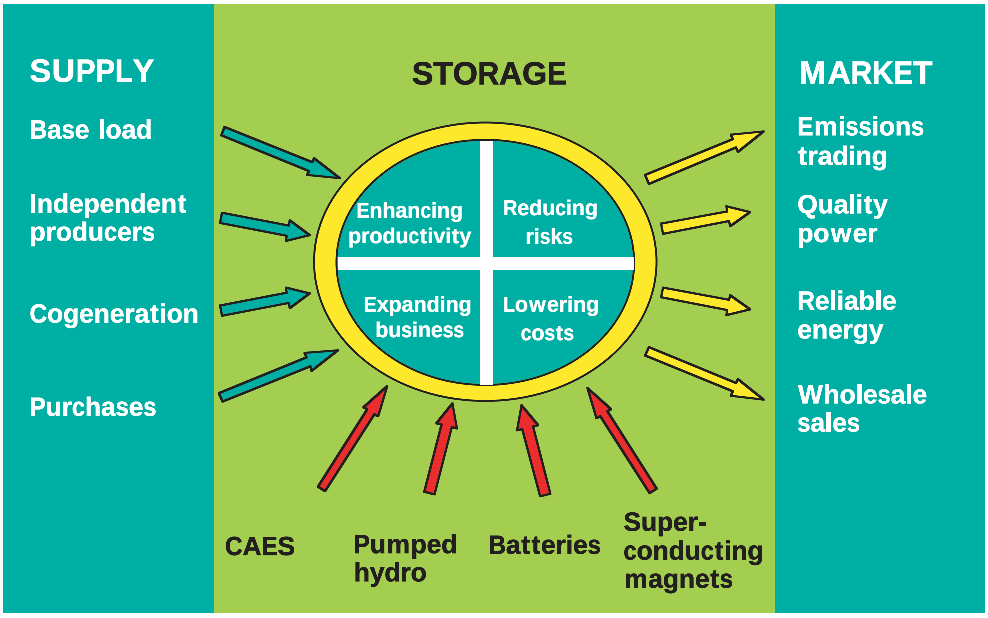


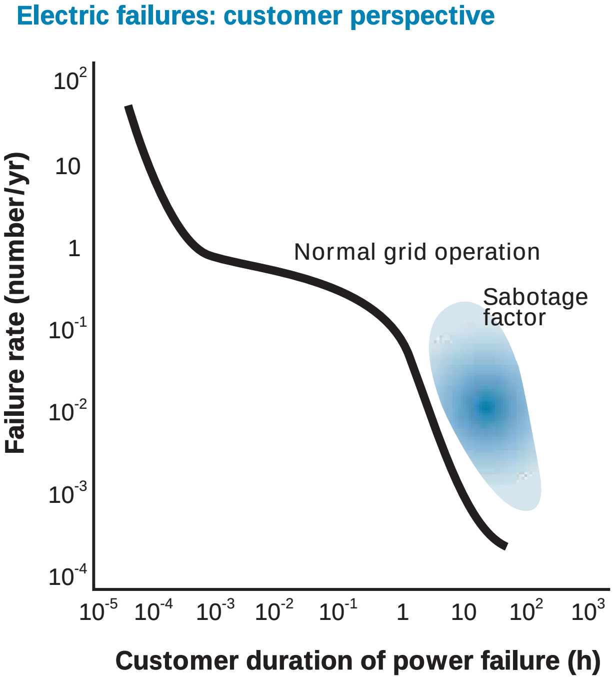
Exhibit 8.6 Strategic benefits of ES in electricity markets (source: ESA)

this $8 million (~£4.2 million), 3-4 year collaborative programme is described in Section 12.5.1.

The technologies under evaluation are a mixture of electronic (advanced capacitors, SMES) and advanced chemical battery technology. Other interests are in the more traditional PHS, CAES and flywheel storage technologies. An important part of this ES mix is the advancement in control systems and telemetry data acquisition systems enabling instant control and balancing in a microgrid arrangement. A practical demonstration of this combination mix is the Palmdale water treatment project described in Section 8.7.3.

8.6 Reliability and security

The supply of electrical power to a user or group of users may be interrupted for a wide variety of reasons, from a major cascading systems failure due to lightning strike, collision between a vehicle and a power cable support pole, to damage to insulators caused by rodents. Data for the frequency of interruptions in the US electricity supply is shown in Exhibit 8.7.



Derived from: "powering the internet-Datacom Equipment in Telecom Facilities" Advisory Comittee of the IEEE International Telecommunications Energy Conference

Exhibit 8.7 Electricity supply failure in the USA (source: IEEE)

Although available published equivalent data on electricity supply reliability for the UK is rather dated (1970s), these data indicate that the average urban user can expect an interruption lasting for one minute or more to occur once every three years, while rural users can expect such an interruption four times per annum. Although efforts are being made to prevent recurrence of cascading faults, the threat of terrorist activity greatly increases the fear of longer and widespread outages.

While utility companies have considered power outages only to be interruptions lasting for several seconds or more, data systems cannot withstand breaks of more than a few milliseconds.

Interruptions in the supply of electricity lose huge amounts of data and revenue: millions of pounds per minute may be lost in the stock market and in major communications hubs.

Owing to the nature of potential faults, it is not possible to provide supplies of sufficient reliability for critical loads via national T&D infrastructure alone: faults may occur too close to the load for this to be a practical solution. For this reason, users of critical loads have adopted various methods of improving the security of their supply, including battery storage, UPS, diesel generators and even privately-owned generating plants.

Local backup is an essential feature of security of supply for critical loads, but segregation of faults is also critical: if a fault is not isolated, it can cause loss of supply to other users and the fault may cascade, eventually leading to a crash of the entire grid. This factor leads to the concept of microgrids.

Further data on US grid resilience and susceptibility to failure are available from the Digital Power Group[8].

8.7 Electricity grid structure and the emergence of ‘microgrids’

8.7.1 US electricity T&D grid

Traditional T&D infrastructure, such as that in the USA and UK, distributes electrical power to users via a network of generating plants, switching stations, substations, power lines and transformers. For electrical efficiency of the grid, electricity is best generated close to the major users of power, but this may not be practical owing to environmental constraints, logistics of fuel supply and, in the case of the UK, international power sharing (high-voltage links between the UK and France, for example).

Resilience of the grid requires that there be duplication of routing of distribution as well as some redundancy in generating plant. While it is expensive to keep generating plant running when it is not needed, the time taken to start large generators from cold means that a certain amount of spinning reserve is essential.

Several forms of local quick-start generators, including diesel and turbine-driven sets, are located at strategic points to provide local enhancement in resilience.

The generic structure of the electricity grid in the USA is shown in Exhibit 8.8.

Following the cascading faults which have recently occurred in North America, Europe and New Zealand, more attention is being paid to ‘islanding’ portions of the grid, such that the associated loads are shed at the same time as faulty portions of the grid, in order to prevent the load from adding to that required to be supplied by the remainder of the grid. Such a technique leads to the proposal that even smaller portions of the grid should be able to operate in isolation, providing security for the associated loads while eliminating cascade effects.

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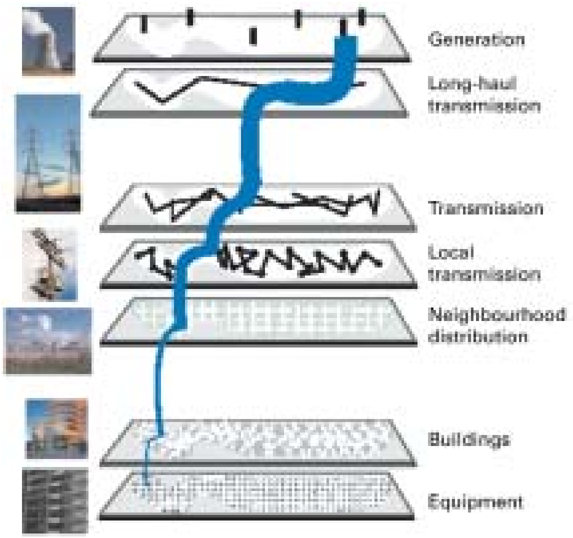
[8] Digital Power Group. *A White Paper On Critical Power.* www.digitalpowergroup.com/Downloads/Critical%20Power%20White%20Paper.pdf



Derived from 'Distributed Energy Resources Interconnection Systems,' US DOE NREL (September 2002).

Exhibit 8.8 Tiers of the US electricity grid (source: NREL)

Many users of critical loads have installed backup systems, generally using diesel generators as the main source of power. While RE sources may be preferred for political and environmental reasons, a diesel generator running on fossil fuel can provide 100 times the power in 1/100 the space required for an RE source and its means of storage of the same rating and duration. In order to avoid the need to keep diesel generators running continuously, while ensuring that there can be no break in the AC supply, however short, means of 'ride-through' is required. This ride-through is provided by UPS or by conversion to DC and storage in a battery for use by DC loads such as telephone systems.

8.7.2 Microgrids

Increasingly, particularly in the USA, the electrical power network of users of critical loads resembles a miniature version of the grid, hence the term 'microgrid'. A typical arrangement of a microgrid is shown in Exhibit 8.9.

In order to be secure and capable of operating in isolation from the main grid, microgrids need to contain means of generation, storage and distribution. Alarms and monitoring systems would normally be included, to be monitored locally and/or remotely. Generation and storage of electrical energy in the microgrid may be by any of the means listed in previous sections, but preferred means of storage include diesel fuel, natural gas or batteries. Flywheels may be used for short stand-by times.

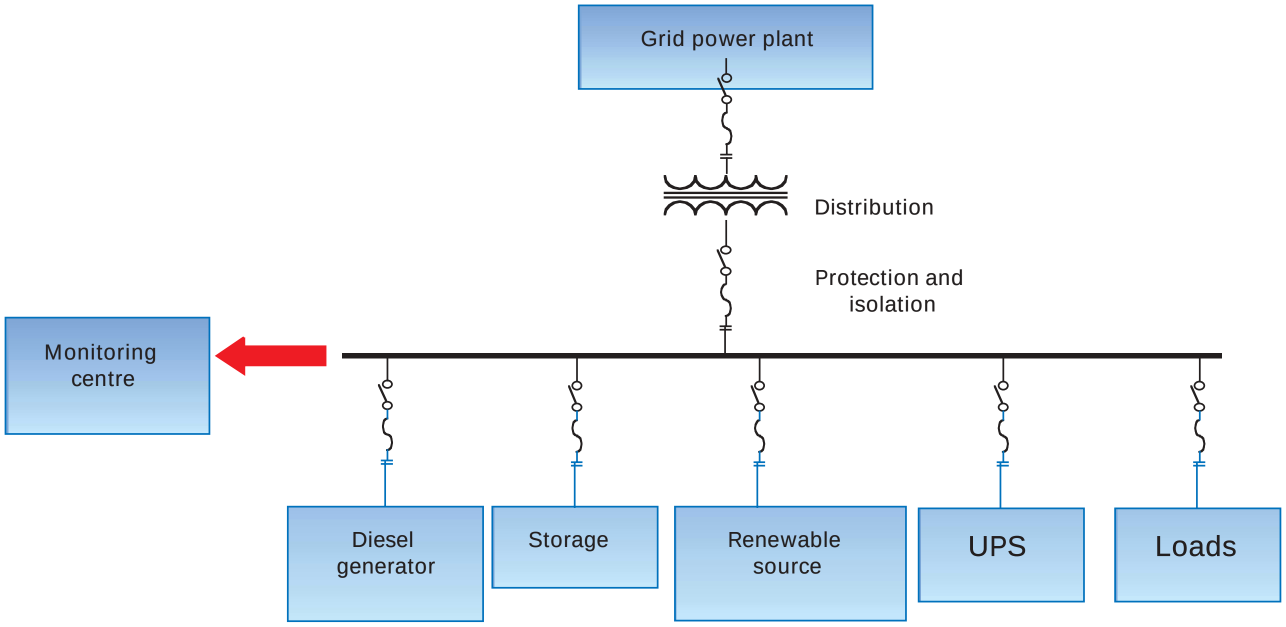


Exhibit 8.9 Typical microgrid arrangement

Currently, many microgrids are designed for a one-way power flow only (ie they are capable of supplying power to their loads, but not back into the grid).

Use of microgrids to supply energy to the national T&D grid ('back-feeding') provides a method of reducing the spinning reserve of the grid if correctly managed, and a source of revenue to those providing the energy. Although many of the microgrids have small capacity, the total capacity is significant: in the USA, around 10% of the national grid capacity is duplicated by 'off-grid' backup.

Legislation requires that the microgrid be isolated from the utility supply automatically when faults occur on the local grid, in order to protect technicians working on the lines. Over-sensitivity in the means of detection means that use of the available capacity of the microgrid is unnecessarily prevented, reducing the ability of the system to reduce the spinning reserve.

A vision of the power system of the future has been developed by the Consortium for Electric Infrastructure to Support a Digital Society (CEIDS, see Section 13.2.3) – a cross-industry body. CEIDS is promoting a vision that exploits ES and stand-by reserves wherever they are located in the network hierarchy. Such a network should be:

- **Self-healing** and adaptive, utilising real-time control
- **Interactive** with consumers and markets
- **Optimised** to make the best use of resources and equipment
- **Predictive** (through intelligence monitoring), rather than reactive to emergencies
- **Distributed** at national, regional and local levels and across organisational boundaries
- **Integrated**, merging monitoring, control, protection, maintenance and marketing using IT
- **Secure** from attack

A body of research institutions has formed a lobby group known as the Consortium for Electric Reliability Technical Solutions (CERTS). This consortium is made up of representations from the University of Wisconsin – Madison, SNL, Georgia Institute of Technology and Lawrence Berkeley National Laboratory, California. An investigation and report has been produced for the DOE proposing the adoption of micro- and macrogrid networks which monitor, maintain and generate power at a more balanced local level, and in the event of a regional or national event either produce a stabilising effect or disconnect as an independent self-generating island.

An initiative of the DOE's Office of Electric Transmission and Distribution (OETD, see Section 12.1.1), referred to as 'GRID 2030', brought together 65 senior executives representing the electric utility industry, equipment manufacturers, IT providers, federal and state government agencies, interest groups, universities and National Laboratories in April 2003 to discuss the future of North America's electricity T&D infrastructure. As well as identifying the critical importance of accelerating the technology readiness of lower cost electricity storage technology, GRID 2030 developed a conceptual design of an electricity T&D infrastructure comprising a national electricity 'backbone' for coast-to-coast power exchange, regional interconnection and local distribution, mini- and microgrids.

8.7.3 ES-enabled renewable microgrid networks

A practical demonstration of the use of ES technology to enable the integrated use of a range of RE sources and direct generation in a microgrid is currently under way at Palmdale Water District, California. The demonstration is illustrated schematically in Exhibit 8.10.

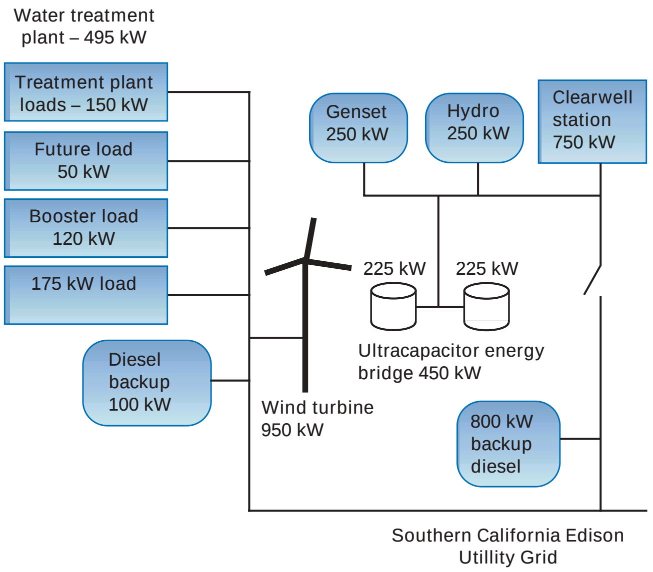


Exhibit 8.10 Palmdale Water District ES-enabled microgrid concept

This project is to integrate a 950 kW wind turbine, a 250 kW hydro scheme and a 250 kW natural gas generator into a microgrid using a 450 kW ultracapacitor ES ‘bridge’ to enable the smooth transfer of RE and direct-generation technologies.

The end-user benefits are seen as:

- Reduced energy cost (exploiting RE sources)
- Improved system reliability (energy bridge and multi-source generation)
- Backup power protection
- Improved power quality

The project impact for the various agencies involved is to apply an ES technology that enables the further exploitation of RE sources at the same time as improving power availability and quality. The storage element is seen as the missing link for integrating RE and direct-generation sources of electrical supply. The total project cost is $2.8 million (~£1.5 million), and installation is due for completion in June 2006. Field trial tests will be undertaken between June 2006 and December 2007.

Exhibit 8.11 Proposed Palmdale microgrid project with 950-kW wind turbine

8.8 Data standards and the role of the integrator

SNL is actively involved as project manager and test certifier in a number of the projects previously mentioned in this report, including the Distributed Energy Test Laboratory (DETL) where the multi-source technology and various ES technology and microgrid components are being tested and evaluated. SNL is recognised throughout the world as having particular expertise in battery evaluation technology and test facilities in combining direct-generation devices from solar, microturbine, wind and fuel-cell energy sources.

DETL is working with other agencies such as EPRI to achieve the CEIDS vision (see Section 13.2.3) of the future through specifying and modelling common data standards such as IEC 61850 SCADA protocols and IEEE 929 (solar) and IEEE 1557 (uniform interconnect standards). The objective is to enable a fully sustainable, interactive and self-healing network.

In discussions with all the US agencies during the course of the mission, it became clear that a major opportunity existed for companies and organisations having expertise in data acquisition and command and control systems that could also take on the role of the system integrator. Clearly, a key enabler to the success of microgrids and the exploitation of ES devices within an integrated network is the ability for the systems to automatically act as a stabilising effect that is intelligently using sustainable energy sources.

8.9 Key messages

From discussions, a number of key issues were highlighted:

- The importance of reliable power supplies in today's digital economy
- The key enabling function of ES in support of grid reliability in an RE environment
- The microgrid vision of the future that links stand-by capacity and ES to grid capacity
- The possibilities that these technologies and concepts could bring to users of large-scale critical power systems (eg telecoms, banking, data centres and healthcare)

9 TRANSPORT APPLICATIONS

9.1 Traction batteries for electric and hybrid electric vehicles

9.1.1 Electric vehicles (EVs)

The market for EVs hasn't progressed as fast as had been hoped in the last ten years or so. This is surprising, given that battery technology has progressed significantly in the last decade. However, vehicle manufacturers have been somewhat reluctant to incorporate new battery technology in products.

Three main types of battery are currently used in EVs:

- Lead-acid (LA)
- Sodium-nickel chloride ('Zebra')
- Lithium-ion (Li-ion)

There are of course other types of batteries, such as nickel-metal hydride (Ni-MH), that work well in EVs, but these have yet to find widespread application.


Exhibit 9.1 VW Golf EV using LA batteries

The German manufacturer Volkswagen AG (VW) offers a typical four-passenger LA-powered VW Golf (shown in Exhibit 9.1). It is lively to drive, with about 180 horsepower, and works very well for commuting. The total cost for the battery modules in this car is said to be around $1,400 (~£740). The range is adequate – about 60 to 70 miles.

The sodium-nickel chloride battery, also known as the 'Zebra' battery, is an advanced technology that is now coming to market. With 120 Wh/kg, the specific energy is four times that of LA. The price in low volume is $500/kWh (~£260/kWh). For high volume, the price is likely to be around $250/kWh (~£130/kWh). Battery life is at least 1,000 cycles, and calendar life is expected to be at least three years.

Li-ion batteries hold much promise for EV application. The best Li-ion batteries pack 40% more energy per kilogram than the Zebra battery, and five times as much as LA. To date, most applications for Li-ion batteries have been for consumer products (see Chapter 10).

9.1.2 Hybrid electric vehicles (HEVs)

In the last few years, Toyota, Honda and Ford have introduced HEVs into the market, and these vehicles (particularly the Toyota Prius) have made some impact.

The growth of this market is, however, in large part related to the battery systems required by HEVs.

The key market drivers for commercial batteries in HEV applications are:

- Cost
- Performance (ie energy and power)
- Safety
- Weight
- Volume
- Cycle-life

The main barriers to the commercialisation of a large number of HEVs are the cost and performance of batteries used to power them: hence there is a strong drive to develop high-energy/power advanced batteries that utilise cheap materials. Thus the relative ranking of the drivers listed above will depend on the application, but they are all desirable.

However, with oil prices currently (and likely to remain) high, the prospects for reduced emissions offered by HEVs, good early customer acceptability, and the promise of a low cost base, significant growth in HEV uptake is predicted – creating a $1 billion market for batteries by around 2010. This projected growth, and the likely battery technologies that will make up this market, are shown in Exhibit 9.2.

It is interesting to compare the Toyota Prius with the fuel cell powered Ford Focus developed as part of the US FreedomCAR initiative (see Section 12.1.2). Both are compact four-door sedans and have essentially the same driving range. However, the Prius HEV weighs around 300 kg less than the Ford FCV. Furthermore, the Prius power system takes up less volume than the Ford's fuel cell power system, resulting in more interior room and a much bigger trunk. If the Ford was refuelled with hydrogen produced with electricity, it would take 240 kWh to produce the 4 kg of hydrogen it needs to refuel. The Prius HEV's battery pack would need only 38 kWh – for the same driving range – as shown in Exhibit 9.3.

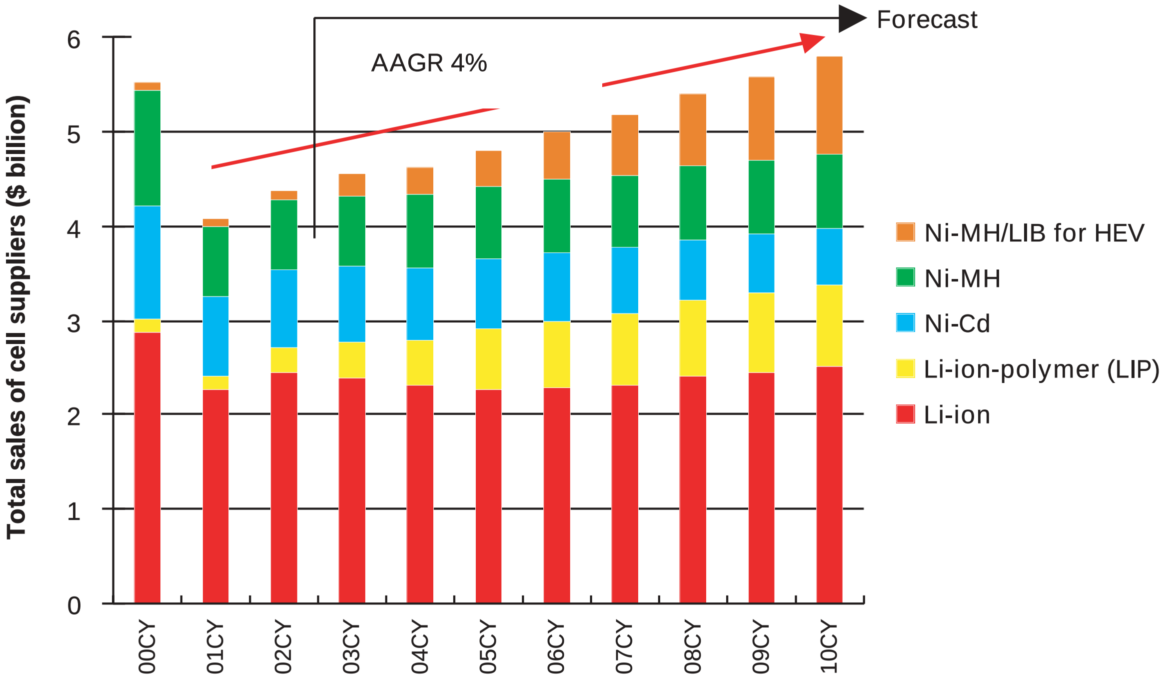


Exhibit 9.2 Projected growth in sales of various rechargeable battery technologies for HEV applications

	Ford Focus FCV	Toyota Prius HEV
Range (miles)	200	150-200
Energy storage	4 kg hydrogen	34 kW Li-ion
Kerbside weight (kg)	1,600	1,300
Electrical energy to refuel (kWh)	240	38

Exhibit 9.3 Toyoya Prius HEV compared to Ford Focus FCV

It is interesting to note that if the Prius HEV were loaded down with more Li-ion batteries to equal the weight of the Focus FCV, it would have around 400 miles range.

It seems, therefore, that HEVs based on the same platform as FCVs can have at least similar, if not greater range than the fuel cell version if the latest battery technology is employed. Points to bear in mind when considering this conclusion are:

- Making hydrogen with electricity is very inefficient. Compared with battery electric vehicles, electricity consumption will be from three to six times higher per mile

- When hydrogen is produced from natural gas, FCVs can, at best, only match the fuel economy of a comparable natural gas hybrid vehicle, and will have less than half the driving range for given tank volume and pressure

9.2 Transport applications of ultracapacitors

In EV and HEV applications, ultracapacitors are increasingly being used to provide burst power for acceleration or climbing, and to scavenge power that would otherwise be lost through braking or deceleration. The use of ultracapacitors to reduce demand on the vehicle battery during times of peak current demand extends battery life. Since the battery is one of the most expensive components in an HEV/EV, the use of ultracapacitors has clear potential to save the customer money. The rapid recharge capability and efficiency of ultracapacitors also makes them well-suited to capturing regenerative braking energy, thus extending the range of an EV. Ultracapacitors have been shown to significantly improve power management in HEVs and extend battery life. In addition, ultracapacitors are claimed to reduce emissions, improve fuel efficiency, and provide advanced electrical drive capabilities.

Pressure for more environmentally friendly means of transportation is leading automotive manufacturers to develop alternatives to existing fossil fuel-driven vehicles. Perhaps the most promising near-term alternative to FCVs, which will not be ready for volume production for at least a decade, is HEV technology. While progress has been made in control, engine and motor design, no satisfactory electric power storage system has yet been developed. This is primarily due to the fact that batteries are used to provide the power peaks in most current HEVs.

Batteries have a bad low-temperature performance, and a limited lifetime under extreme conditions, which results in repeated replacement throughout the life of the vehicle. Batteries are also not designed to satisfy the most important requirement of an HEV power source: to provide bursts of power for events such as acceleration, braking, and cold starting.

The use of ultracapacitors to improve ES in automotive applications in combination with an electrochemical battery offers a viable design approach. Ultracapacitors are available in a variety of sizes and a variety of configurations. Ultracapacitor prices are now within the cost target for many automotive systems, and in 2004 were approaching $0.01/farad in automotive production volumes.

As noted earlier, ultracapacitors offer good performance, a wide operating temperature range, and long life. When used in combination with other ES solutions (eg LA batteries, internal combustion engines, fuel cells), the complete system can meet performance and cost goals unachievable with a single ES device.

In terms of energy density and access time to the stored energy, ultracapacitors are placed between large aluminium electrolytic capacitors and smaller rechargeable batteries[9].

Peak power applications in automotive engineering need passive components to store electrical energy that are as small as possible in volume and weight. The choice of storage device depends particularly on the speed of the storage process, or in other words on the power required by the application. While the slower storage processes may be performed with batteries, and the faster ones with conventional capacitors, the ideal storage device to supply bursts of power in the seconds range does seem to be the ultracapacitor.

Existing and new applications include automotive engineering, public transport, forklift trucks and rail traction vehicles. Numerous automotive firms are well into the production design cycle for ultracapacitor-based powertrains and subsystems, and there appears to be widespread recognition of the advantages and availability of the ultracapacitor to meet business and technical requirements.

9.2.1 Ultracapacitors used in EV, HEV or HEFC vehicles

In recent years, numerous hybrid drivetrains have been proposed. An interesting concept is that of the fully-electric hybrid drivetrain, consisting of a primary, constant-power source, such as a fuel cell or a battery, and a secondary, peak-power source, such as an ultracapacitor array[10]. The primary power source handles continuous load requirements, such as cruising, as well as basic electric needs. The secondary power source is sized for short-duration load-levelling and absorbing kinetic energy from braking (regeneration).

Regeneration has been shown to result in energy savings of up to 25%[11], and increased range of the vehicle. Because short-duration regeneration events are experienced many thousands of times throughout the life of a vehicle, they are well-suited for ultracapacitors.

In collaboration with VW and other partners, a demonstration hybrid electric fuel cell (HEFC) vehicle has been designed incorporating an ultracapacitor ES device[12,13]. The ultracapacitor bank used is capable of providing a constant power of 50 kW during 15 seconds of discharge from full- to half-rated voltage. This is equivalent to an energy content of 210 Wh at 50 kW.

9.2.2 Integrated starter-generators

Many automotive subsystems that have traditionally been mechanically powered are now electrically driven. Examples of

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[9] A Burke and M Miller, *Characteristics of advanced carbon-based ultracapacitors,* 10th international seminar on double-layer capacitors, Deerfield Beach (2000)

[10] E Faggioli, P Rena, V Danel, X Andrieu, R Mallant, H Kahlen, *Supercapacitors for the energy management of electric vehicles,* J of power sources, 84: 261 (1999)

[11] Ph Desprez et al, *Supercondensateurs: un tampon de puissance pour sources d'énergie,* Colloque Piles à combustible et Interfaces pour les transports, Belfort (2000)

[12] P Dietrich et al, *Supercapacitors for peak-power application with fuel cell system,* Proceedings of the 2nd BOOSTCAP meeting, Fribourg, Switzerland (29 March 2001)

[13] R Kötz et al, *Supercapacitor for peak-power demand in full-cell-driven cars, ECS Proceedings,* PV 2001-21, Electrochemical Society Inc, Pennington, NJ

this include electric power steering, electromagnetic valve control, electric coolant pumping, electromechanical braking, electric air conditioning, electric door opening and locking and catalyst preheating, as well as the introduction of new drivetrain functions such as engine start-stop and regenerative braking. It has been shown[14] that storage of braking energy can also be usefully applied to conventional vehicles with ICEs, with an improved alternator (known as a starter-generator) used also for braking. Conventional LA batteries cannot rapidly make energy available (in a few-seconds timescale) because of the relatively slow nature of chemical processes. Ultracapacitors, however, can store energy within a very short time, and release it with high efficiency, even in cold weather.

9.2.3 Regenerative braking

In conventional vehicles, up to 25% of the total energy provided by the fuel is converted to heat during braking. As noted earlier, regeneration has been shown to result in energy savings of up to 25%, and increased range for the vehicle. The effect is even more critical in urban traffic. Introducing a system to allow braking energy to be stored is an obvious step, allowing the capture of energy that would otherwise be lost for reuse in subsequent acceleration. Such systems offer improved fuel consumption in urban traffic, where stop-and-go is very common. Regenerative braking is also essential to extend the range of EVs. However, this method of energy saving can also be usefully applied to vehicles with ICEs.

9.2.4 Buses

Buses are pioneering vehicles for environmentally friendly transportation. Until fuel cells go into volume production, combustion engine-electric drives currently represent the most successful ‘clean’ drive systems to reduce the emission levels of buses. Typically these combine a diesel engine with an electrical powertrain. Claimed advantages of these diesel-electric drives include low fuel consumption, reduced emissions, and quieter running during starting and part-load operation. Ultracapacitors have been used on a number of bus projects as the ES medium for regenerative braking.

On a larger scale, ultracapacitors are well suited to many transportation applications. The endless cycles of acceleration followed by braking, of mass transit train, subway and metro systems are ideal for ultracapacitor technology.

Several projects are running in the field of transportation applications, for example, a tram supply without catenary, and a voltage-drop compensation for weak distribution network[15].

9.2.5 Engine starting with ultracapacitors

Ultracapacitors cannot replace the conventional car battery, but they do extend its application range significantly. They ensure reliable starting when this must be done frequently or in case of low temperatures, where they improve the vehicle’s cold starting properties by increasing the starter torque and stabilising the automotive power system voltage. Even if the battery output is low, the peak power needed for starting can be supplied by ultracapacitors connected in parallel to the battery. This allows a smaller battery to be used.

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[14] R Schöttle, G Threin, *Electrical power supply systems: present and future,* VDI Berichte, Nr 1547 (2000)

[15] A Rufer, *Key developments for supercapacitive energy storage: power electronic converters, systems and control,* 2nd BOOSTCAP meeting, Fribourg (2001)

10 PORTABLE APPLICATIONS

10.1 Batteries for portable/lightweight applications

The world market for batteries is approximately $43.0 billion (~£22.6 billion) in total and is growing at about 7% annually. A key area of growth has been in the sales of Li-ion batteries which, since their emergence in the early 1990s, have exhibited very high growth and now account for around $4.5 billion (~£2.4 billion) of this market. This strong growth looks likely to continue.

The main driver for this remarkable growth has been the so-called 'cordless society', where users demand complete freedom from mains-based electricity. This has led to the huge growth in the use of portable devices, including:

- Mobile phones (773 million units/year: >90% Li-ion battery)
- Laptop/notebook computers (343 million units/year: >95% Li-ion)
- Digital cameras (60 million units/year: >95% Li-ion)
- Camcorders (15 million units/year: >90% Li-ion)
- PDAs/organisers/'smartphones' (15 million units/year: 90% Li-ion)

These applications provide the strongest drivers (size, mass and run-time command a premium) and can accept the relatively high cost of advanced batteries such as Li-ion.

This market growth for batteries for portable applications is shown in Exhibit 10.1.

The 'value chain' for the Li-ion battery industry is presented in Exhibit 10.2. This chain is dominated by the cell manufacturers and the OEMs. Several of the key OEMs are also cell manufacturers (eg Sony, Sanyo and Panasonic), and the high-volume markets are dominated by Asian companies or companies manufacturing devices in Asia (eg Nokia).

In specialist markets, independent battery assemblers play a significant role: they purchase cells from cell manufacturers and design and make battery systems. However, these are often restricted to 'standard' cell designs used in the high-volume markets. There are a very small number of companies making Li-ion cells for the specialist markets (eg Saft).

Japanese cell manufacturers (including Sanyo, Sony, MBI/Panasonic, NEC, GS-Sony and Maxell) dominate the Li-ion market, although Japanese market share has fallen from 95% in 2000 to 67% in 2003: they are looking for new, low-cost, high-performance technology to maintain this market share. Chinese manufacturers (including BYD, Lishen, B&K and ATL) have increased their market share to 19% through aggressive pricing based on manual/semi-automated production; Korean players (including Samsung SDI, LG Chemical and SKC) have gained a 13% market share but need improved technology to avoid being squeezed in the middle.

As is the case in transport applications, the key market drivers for commercial batteries are:

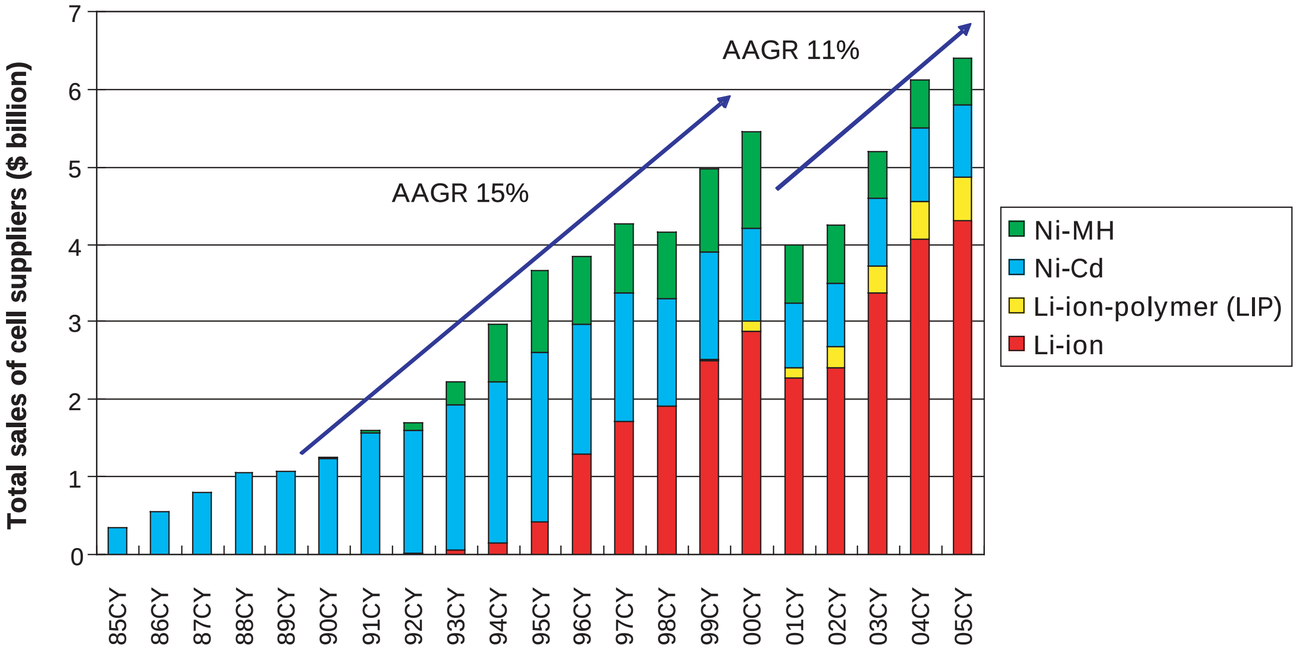


Exhibit 10.1 Growth in sales of various rechargeable battery technologies for portable applications

- Safety
- Weight
- Volume
- Cost
- Performance (energy and power)
- Cycle-life

For commercial batteries in most portable applications, consumers will ideally prefer batteries that have a long run-time and are cheap (as the cost of the battery generally contributes significantly to the cost of the device) and weigh very little.

Safety is also an issue for battery manufacturers and OEMs as they do become liable for huge fines when accidents occur in commercial devices using their batteries. Li-ion cells which utilise $LiCoO_2$ cathodes need control electronics to prevent overcharge. Overcharge of Li-ion cells can generate lithium metal which poses a fire and/or explosive hazard on repeated cycling. Safety incidents involving consumers have in the past led to battery products being withdrawn from the market and indeed to closure of entire factories.

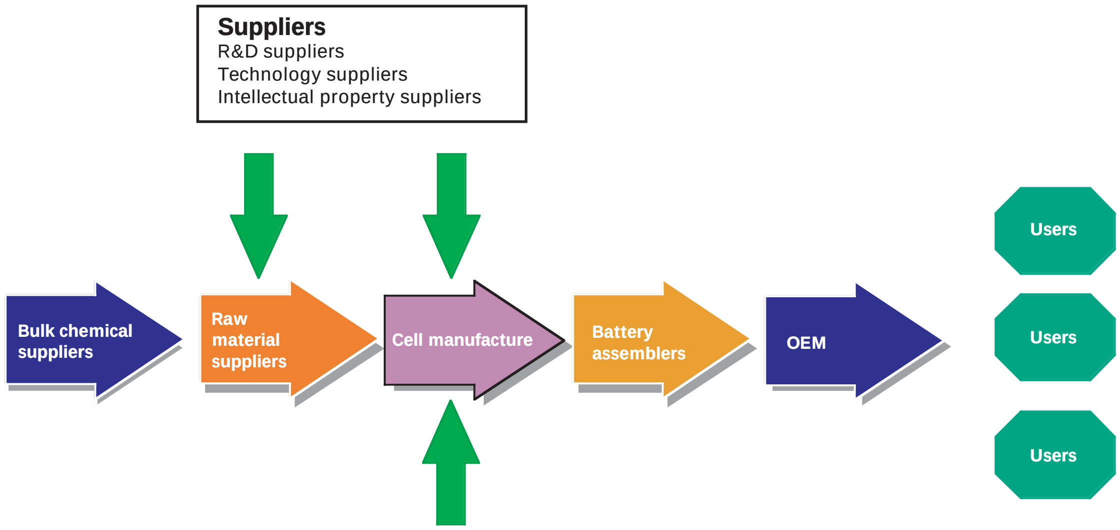


Exhibit 10.2 Value chain for the Li-ion battery industry

There is also increasing emphasis on the need to recycle battery materials once they have been spent.

10.2 Ultracapacitors for portable/lightweight applications

As the need for smaller and more lightweight systems increases, design engineers require innovative design approaches to reduce size and weight. This is especially true for portable products such as laptop computers and mobile phones. The heaviest component in many portable designs is the battery. As the main source of power in most portable products, finding an ideal battery in terms of size, weight, and performance represents an ongoing challenge.

In applications requiring relatively static amounts of power (such as calculators, watches, and portable radio applications) a battery or set of batteries is generally sufficient to supply a small amount of current over a reasonable amount of the product's lifetime. However, in applications where there is additional short-term demand for high power – ie, for a large amount of current over a short period of time – batteries have proven to be less than satisfactory.

Ultracapacitors have been used in two major ways to address this need. The first is for temporary backup power in electronic devices, for functions such as computer BIOS settings, telephone and camera configuration settings, and secondary short-term emergency power. Here the ultracapacitor is charged from the primary power supply, but functions as a backup power source when the primary source fails.

The second use for ultracapacitors is for supplying peak power in electronic devices. In these applications, ultracapacitors are used in tandem with batteries for systems that require both a constant low-power current for continual function, and a pulse power to meet peak loads. Ultracapacitors can be used to relieve batteries of peak power demands, resulting in an extension of battery life, reduction of overall battery size and weight, and reduction in product size/weight.

In a digital camera application, representative of a typical ultracapacitor-enhanced design (in this case using two Maxwell Technologies' PC 10 ultracapacitors), ultracapacitors work with a battery to provide overall system power management. The ultracapacitors power the initialisation of the camera, and drive functions involved in composing photographs, such as microprocessor, zoom, and flash functions. The peak demands occur during microprocessor activity, writing to disk, and LCD operation. By providing peak power functions, the ultracapacitors level the load on the battery.

It can be seen that by connecting ultracapacitors across the alkaline batteries, the cycle-life is drastically increased (Exhibit 10.3). It was found that the addition of ultracapacitors allowed inexpensive alkaline batteries to achieve the same life cycle as expensive, high-power batteries. By using the ultracapacitor in parallel with the alkaline batteries, the overall system impedance reduced, allowing the battery to act as a pure energy source. Thus, replaceable, low-cost, off-the-shelf alkaline batteries can be used, making the camera smaller and lighter.

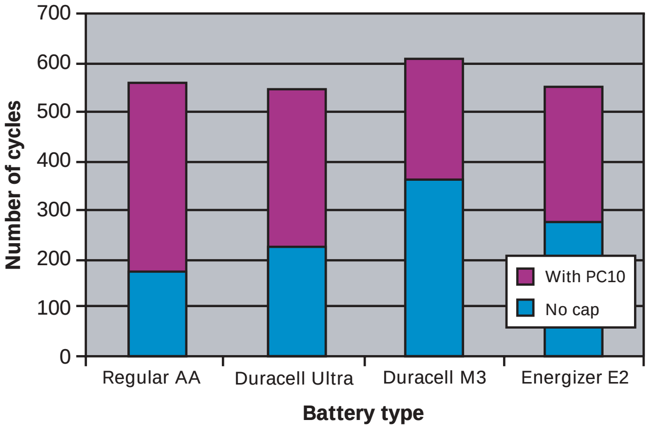
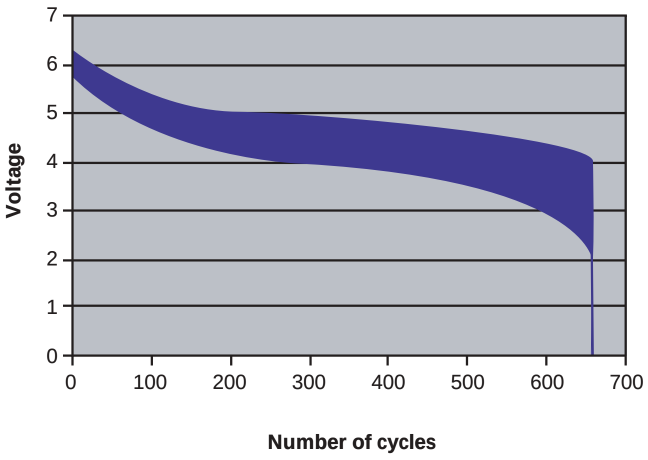
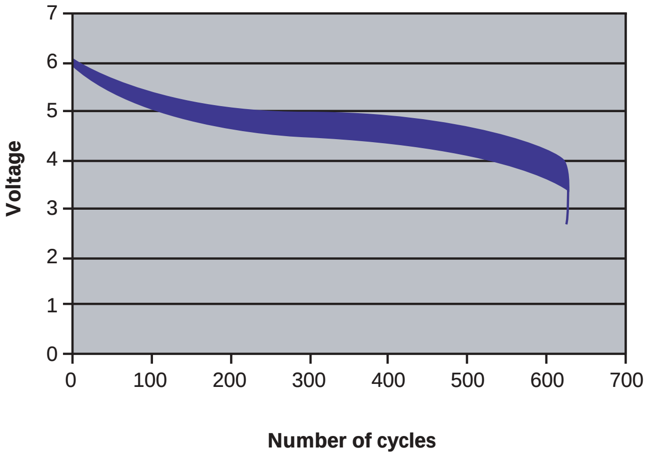


Exhibit 10.3 Cycle-life of several different batteries, with and without ultracapacitors (source: Maxwell Technologies)



(a) Batteries only



(b) Batteries and ultracapacitiors

Exhibit 10.4 Voltage swing for typical digital camera cycles: (a) batteries only; (b) batteries and ultracapacitors

The graphs in Exhibit 10.4 show the voltage swing for typical digital camera cycles. As indicated, the voltage drop increases rapidly with batteries only, but when an ultracapacitor is placed in parallel in the system, the entire voltage drop is decreased and maintained.

Battery-operated toys are an increasingly important application for ultracapacitors. In the toy industry, cost is critical. Toy companies will explore every option to reduce expenses and increase margins. After price, toy manufacture requirements include product availability and performance. Toy manufacturers can benefit by placing a permanent ultracapacitor on board in place of a battery. A major advantage is that an ultracapacitor is much lighter than a battery, and can be recharged many hundreds of times from a battery pack. Small cells with a flat design, such as Maxwell's PC5 and PC10 devices, are proving especially popular for toy applications.

Other current and potential portable ultracapacitor applications include two-way pagers, GSM-protocol cell phones, hand-held GPS systems and power tools. As the demand for smaller portable devices increases, the flexibility, durability and power of the ultracapacitor seem likely to play an increasingly important role in helping designers to enhance product functionality, while simultaneously decreasing size.

11 MILITARY APPLICATIONS

The military of every nation uses a large quantity and variety of electrochemical power sources: it has been estimated that throughout the UK armed forces, over 6,000 different types of batteries are in use and that even a single paratrooper may be carrying up to 16 different types of battery.

Advanced batteries could have a significant effect on military effectiveness and, for some applications, the lack of suitable batteries is the greatest limiting factor.

One of the areas in which the lack of advanced batteries will reduce fighting capability is in the future dismounted soldier. Future soldier programmes such as ‘Integrated Soldier Technology’ (IST) in the UK, and ‘Land Warrior’ and ‘Future Force Warrior’ (FFW) in the USA, are limited by the power sources currently available. The constraints of current battery technology are limiting the endurance of a mission and the amount of electronic equipment which can be utilised.

Despite improvements in portable electronics and power management, it is likely that the demands for power on the dismounted soldier will increase well into the future as further functionality is desired. This is graphically illustrated in Exhibit 11.1.

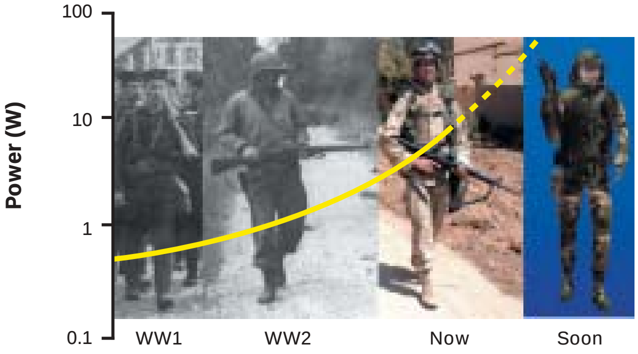


Exhibit 11.1 Trend of increasing power demand of the foot soldier

Another challenge facing power sources for the military is the development of a rechargeable battery which is light enough whilst containing enough energy to power UAVs (unmanned aerial vehicles). The concept for long-duration UAVs is to have the platform powered by photovoltaics (PV) during the day, which also charges batteries to power the platform at night. Hence, for this application, the batteries need to be rechargeable and lightweight.

Submarines utilise very large batteries to provide emergency power – a typical nuclear submarine will use several MWh of LA batteries. Whilst these are adequate for the job, they must be monitored regularly and replaced every five years, which is an expensive undertaking. Advanced batteries have the potential to improve performance and reduce through-life costs since the majority of the technologies under development offer significantly longer lifetimes.

Submarine applications are different to most other military applications, since it is generally the volume of the battery and not the weight which is the most limiting factor. For new designs of submarines, a more energy-dense battery system would free up significant volume which could either be used for other systems or could reduce the overall hull size. It is likely that advanced batteries could more than halve the size of the required battery compartment.

Other military areas in which electrochemical power sources such as batteries, fuel cells or capacitors are, or may become, important are:

- Hybrid electric combat vehicles
- ‘Silent watch’ and auxiliary power units (APUs)
- Pulse power weapons
- Unmanned underwater vehicles
- Sensors

11.1 Defence drivers

The drivers for defence power sources are not dissimilar to those for commercial power sources, although because of the expense of the equipment on which they will be used, a higher cost can generally be tolerated if it will lead to performance enhancements or cost savings elsewhere. This is not to say that cost is not important to the military, but that the cost of the power source will generally be a smaller fraction of an equipment capability. Some key military drivers are as follows:

- Safety
- Weight
- Volume
- Cost
- Power
- Energy
- Operating temperature

Ideally the military would like a cheap, lightweight, small power source with high energy and power capability at low cost. The relative ranking of these drivers will depend on the application but they are all desirable.

11.2 Mission visits to military establishments

As part of the mission to the USA, visits were made to a number of US military research establishments. Traditionally, the military have been seen as early adopters of new technologies, and since there is a desperate military need for improved power sources, these establishments have some world-leading technology.

The establishments visited and key technologies under development are discussed below.

11.2.1 TARDEC (Tank-Automotive Research, Development and Engineering Center), Detroit Arsenal, Warren, MI

TARDEC’s mission, organisation, staffing and funding are described in Section 12.2.1.

Due to the current situation, their work has undergone some refocusing, with more effort having to be spent addressing immediate vehicle issues for the current conflict in addition to developing future combat vehicles.

TARDEC supports over 2,800 field systems, including the Abrams tank, Bradleys, ‘Humvees’ (or more correctly, HMMWVs – high-mobility multipurpose wheeled vehicles) and diverse systems such as fuel logistics, water purification, countermine vehicles and fuel and lubricant technologies.

TARDEC's interests can be broken down into a number of categories –

- Mobility
- Pulse power
- Engines
- Fuel cells
- Suspension
- Active defence
- Intelligent systems
- Water purification

– which are now reviewed in turn:

Mobility

TARDEC is investigating HEVs for both combat and tactical use. It is expected that the next generation of combat vehicles will be HEVs with large quantities of exportable power and with electric subsystems replacing the hydraulic systems. It was stated that hydraulics are one of the major sources of fire on combat vehicles. It is also anticipated that 10% of the new Humvee class of tactical vehicles will be HEVs to provide further exportable power and remove the need for trailer-based generator sets. Cost will prevent the rest of the tactical fleet becoming HEVs unless an argument can be made in terms of fuel economy for HEVs.

The demonstrator vehicles, with 30 kWh of on-board electrical storage, are currently using Saft Li-ion cells. Boeing is developing the next generation vehicles and will put the battery contract out to tender. TARDEC would be interested in seeing improvements in the power levels of the batteries since preliminary tests have highlighted some issues at high powers.

Ultracapacitors have been investigated, and TARDEC believes they may have some place on tactical vehicles for starting but that the energy requirements of combat vehicles preclude their use for ES. TARDEC has not yet investigated ultracapacitor-battery hybrids, but intends to do so.

Pulse power

TARDEC is investigating electromagnetic armour in collaboration with the UK MOD. It is believed that it is very likely that this will be fitted to the next generation of combat vehicles, and possibly even retrofitted to existing vehicles if feasible. The number two threat in the current conflict is RPGs (rocket-propelled grenades), and protection against these is a high priority. The number one threat is IEDs (improvised explosive devices). Rail guns are also being investigated but are not foreseen as being deployed on the next generation of vehicles.

Engines

Engines to power generators are being investigated, and TARDEC is working with two overseas companies – Ricardo and MTU.

Fuel cells

Fuel cells are being funded at a relatively small level of less than \$10 million (<£5.3 million) per year, although this may increase to \$20-30 million (£11-16 million) in coming years. They are not seen as providing vehicle propulsion for next-generation vehicles, but rather as APUs. It is believed that this can reduce some of the fuel wasted by trucks idling in the tactical fleet, and also might provide power for battery charging and silent watch for the combat fleet. Regenerative fuel cells and the on-board reformation of logistical fuels will be investigated.

TARDEC recently held an industry briefing day at a fuel-cell seminar in Texas (November 2004), where it stated that the goal for its fuel-cell team is to develop and test a laboratory brass board of a 5-20 kW APU system for military applications. The main focus of this effort will be the reformation of JP-8 fuel.

Suspension

Another area of research is in PC-controlled advanced suspension. Concepts such as magnetorheological fluids, bypass of damping circuits and full electromagnetic suspension have been investigated. Many of these are regenerative, so it is power and not energy which is the issue. TARDEC has built a Humvee, a 2.5-ton truck and a 20-ton combat vehicle demonstrator. Controlled suspension provides the ability to raise and lower the vehicle, which can give a lower profile when inactive, and improve survivability. Pitch and roll control provides for better accuracy of mounted guns. Additionally, there is the desire for command-and-control to be vehicle mounted and enabled whilst on the move. Motion sickness is a major problem when operating PCs etc in the back of a rolling vehicle.

Active defence

Power will also be required for active defence, such as electronic warfare including jammers and decoys, and active protection to kill incoming weapons. In the distant future, high-energy lasers are being suggested for active defence, but this will not be ready for the next generation of vehicles. Signature management is also under investigation, but this could not be discussed in an open meeting.

Intelligent systems

TARDEC has four development programmes on new UAVs, the smallest being a hand-held system. These all currently run from small gasoline engines, although TARDEC is looking to move to JP-8. Small gas turbines may be considered but there is an issue with fuel efficiency, and so in many instances engines will be preferred. Ground robots are also being developed. These include small RF-controlled robots to look under cars, mine clearance robots, and the Talon interrupter for disposal of IEDs. Autonomous robots are considered a much more difficult challenge, and these are not believed to be feasible until the 2010-2020 timeframe.

Water purification

TARDEC also provides the power for water purification plant, which is run by diesel engines. It uses reverse osmosis so is a high power consumer. Also under investigation is a moisture-harvesting device to remove water from the atmosphere, although this will be a high energy consumer. Due to the high power demands, it is believed to be unlikely that these applications could be powered by PV. Water capture from vehicle exhaust systems is also a possibility.

Discussion

Some interesting points were made during discussions. The original Abrams tank used LA batteries and could perform a two-hour silent watch on their capacity. However, the current Abram carries so much electronics that it can barely do a silent watch at all, and in general the engine is never turned off. It is believed that 10-15 kW are required for silent watch, including all the electronics and air conditioning. In fact, two air-conditioning units are required, one for the crew and another dedicated to cooling the electronics.

Another interesting point was made that although there was no desire for a further battlefield fuel in addition to the Dieso and JP-8 currently being used, it is expected that the US Army would accept almost any fuel for specialist long-duration operations such as scouts. Equally, since the cost of deploying scouts into hostile territory is so expensive, the cost of the fuel and system would be less of an issue. It was felt that platforms such as UAVs, UGVs and long-range scout vehicles could accept non-logistic fuels if this gave a significant performance advantage.

However, for the non-specialist vehicles, it was felt to be highly unlikely that the logistic burden of a further fuel would be acceptable. US helicopters now operate on the JP-8 common fuel and no longer use gasoline. The DOE and the US auto industry have decided that on-board reforming of liquid fuels for FCVs is no longer an attractive option. This is in part because HEVs are now seen as a preferable 'bridging technology' to on-board reformers, and also the fact that it would be likely that another super-clean fuel would need to be introduced. TARDEC is still pursuing on-board reforming for military vehicles, and the reforming technologies will need to operate from the JP-8 logistic fuel.

HEVs are being seriously considered by the US Army for the future, and the current view is that the next generation of US combat vehicles will be a hybrid, with 30 kWh of ES. This will provide silent-watch capability and exportable power. A move to exportable vehicle power is anticipated to remove the need for towed diesel generator sets.

11.2.2 ISN (Institute for Soldier Nanotechnologies) at MIT, Cambridge, MA

ISN's structure and funding are described in Section 12.2.1.

ISN's mission is to 'develop and exploit nano-enabled materials, devices, processes and instrumentation to dramatically enhance soldier survivability'. It is focused on the application of nanotechnology to the dismounted soldier, with the goal of creating a 21st-century battlesuit that combines high-tech capabilities with light weight and comfort.

Today's dismounted infantry soldier carries a backbreaking load, usually 45-65 kg, and still has insufficient ballistic protection, little defence against chemical and biological weapons, and too many pieces of equipment that don't work well together. ISN's challenge is to transform today's cotton/nylon fatigues and bulky equipment belts to a sleek, lightweight battlesuit that provides everything from responsive armour to medical monitoring to communications – and more – in one integrated system. ISN envisages a bulletproof jump suit, no thicker than ordinary spandex, that monitors health, eases injuries, communicates automatically, and maybe even lends enhanced abilities. It is a long-range vision for how technology can make soldiers less vulnerable to enemy and environmental threats.

Nanotechnology fits into this vision in two important ways. First, it offers the potential for miniaturisation, a key part of reducing weight. Today's heavy radio, worn on a harness, might be reduced to a button-sized tab on the collar; and a waterproof poncho could be replaced by a permanent nano-thin coating applied to everything the soldier carries. Second, because nanotechnology operates at scales where classical macroscopic physics breaks down, it offers engineers the potential for creating unprecedented new material properties and devices.

Seven teams are addressing various aspects of this challenge through specific research projects now numbering almost 50.

Those teams are:

- Team 1: energy absorbing materials
- Team 2: mechanically active materials and devices
- Team 3: sensing and counteraction
- Team 4: biomaterials and nanodevices for soldier medical technology
- Team 5: processing and characterisation
- Team 6: modelling and simulation of materials and processes
- Team 7: systems design, hardening, and integration

Currently, ISN's remit does not include power sources, although it is a potential area of research for them. As part of the discussions, reference was made to a US report on future power sources for the US dismounted soldier[16], a useful document for comparison with the UK vision.

The institute has some excellent facilities, especially in the field of materials production and characterisation. It has yet to produce a power requirement for the future soldier battlesuit or to undertake any research to solve the power issue, but it has excellent facilities within the institute and throughout MIT should it choose to do so.

An interesting initiative being launched by ISN is a competition for MIT graduates to develop power solutions for the dismounted soldier. This aims to engage the MIT graduate community in solving problems of relevance to the military. One of the challenges is to develop a battery scavenging and recharging system. It is believed that many batteries in the field are discarded whilst still containing residual energy. The target is to demonstrate an electrical scavenging system that can reclaim the electrical energy from an array of used batteries and use this to recharge an 'AA' battery. The threshold target has been set at 100 g for the device, and the objective as 50 g, ie double the weight of an 'AA' battery (~25 g). The system must also weigh less than the equivalent battery weight for the energy it could reclaim. This should reduce some of the electrical energy wasted in the field. If this concept could be adapted to produce a converter to enable any battery to recharge any other battery at will, then this might have even wider use.

Another of the challenges is a portable power-generation system. This is to design a portable, preferably wearable, power-generation system that utilises the soldier's natural energy such as body heat, movement etc. The power generated in this way will be used to recharge an 'AA' battery. The concept of engaging students in military problems is an interesting one and it would be interesting to see if a similar idea could be applied in the UK.

11.2.3 CERDEC (Communications-Electronics Research, Development and Engineering Center), Fort Monmouth, NJ

CERDEC's mission, organisation, staffing and funding are described in Section 12.2.1.

CERDEC's main focus is on power sources for the dismounted soldier. Traditionally, its main areas of research were battery and battery-charger development because they develop and integrate near-to-medium-term technologies. Their aim is not to develop novel battery and fuel cell chemistries but to adapt them and integrate them to meet the needs of the dismounted soldier. Recently, fuel cell and Stirling engine technology has reached a sufficient state of maturity to warrant CERDEC's attention.

CERDEC was instrumental in developing the Zn-air battery system, and this technology is envisaged to form an important part of future battery systems for the US military. This is a primary technology and is predominantly intended to be used as a battery charger for secondary batteries. The Zn-air chemistry does not adapt well to traditional architectures such as the BA5590, and so a new form factor – the BA8180 (Exhibits 11.2, 11.3) – has been adopted.

The Zn-air system can also be used to power the SINCGARS radio for long-duration run-times where this is necessary, and this has been demonstrated by the US Marines. Hybrid systems using Zn-air for long duration, and lithium secondary batteries for high power, are being developed. The new BA8180 form factor developed for Zn-air batteries may now also be used for other chemistries such as Li-CFx.

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[16] *Meeting the Energy Needs of Future Warriors*, US National Research Council, ISBN 0-309-09261-2 (2004): www.nap.edu/catalog/11065.html

Exhibit 11.2 BA8180 Zn-air battery

Nominal voltage	28 V or 2 x 14 V sections
Nominal capacity	27 Ah (@ 24 V)
Size L x W x H	310 x 185 x 60 mm
Weight	2.7 kg
Specific energy	350 Wh/kg
Energy density	240 Wh/L

Exhibit 11.3 Parameters of BA8180 Zn-air battery

A photovoltaic (PV) battery charger, utilising foldable PV arrays made from thin-film coating technologies, has been developed by CERDEC. These are capable of being folded into a flat package about 300 mm square, and can recharge a battery in 6-8 hours. A significant development for the military was the incorporation of a camouflage ink during the fabrication process which removes the glinting of PVs in sunlight, which could give away the position of troops.

Another interesting technology developed by CERDEC was a ruggedised battery charger which can be deployed from a plane and used to charge batteries in-theatre where there is no other logistic chain to do so.

CERDEC has evaluated almost all portable batteries of interest to the US military, both current technologies and technologies under development such as the Li-S cells from Sion Power. It has also assessed fuel cells, both from US manufacturers and from foreign suppliers (such as Smart DMFC, Intelligent Energy (UK), Ballard and IdaTech) under the Foreign Competitive Test and Evaluation Program. They are also evaluating batteries from Europe and Asia under this programme. The results of these studies will be shared with the relevant manufacturers to help them meet US military needs.

A shocking statistic to arise during discussions is that a US soldier now uses, on average, one 'AA' primary battery per hour. CERDEC is investigating quick-charge Ni-MH 'AA' cells, which have the ability to be recharged in less than 15 minutes, to reduce the number of cells required.

It was also noted that care must be taken by equipment manufacturers to ensure correct operation of their devices using batteries that may be found in-theatre. An example of this is that equipment designed to use the now standard commercial zinc-alkali cells that are readily available in the West may have to rely upon the older, lower power Leclanche cells which are still widespread in developing countries.

The technology system solutions envisaged by CERDEC are:

- Sensors – powered by metal-air cells and ultracapacitors

- Dismounted soldier power battery – initially hybrids such as Zn-air with Li-ion (250 Wh/kg system). To try to achieve a 72-hour mission, such as required by the Land Warrior Program, CERDEC expects to use a fuel-cell/Li-ion hybrid. The choice of fuel cells could be direct methanol fuel cell (DMFC), a small methanol reformer and proton exchange membrane (PEM) fuel cell, or solid hydrogen storage in a compound such as ammonia borane combined with a PEM cell

- Battery recharging – which typically requires hundreds of watts. CERDEC envisages that reformed fuel and a fuel cell will be used. The goal is for a small JP-8 reformer, but the technology is not sufficiently advanced at the current time. Small Stirling engines are also under investigation, with a linear piston design showing good improvements in power densities

- APUs – CERDEC envisages either fuel cells or Stirling engines for APUs. Cogeneration could be important since the system could provide the heating and cooling needs of the tactical system. The US Army ideally desires a silent power source operating from a single logistic fuel, although reformer and fuel cell systems are not yet mature enough to achieve operation from JP-8

CERDEC absorbs a lot of its technologies from universities, eg they have been involved with the University of South Carolina on the development of a model for a 'Humvee' using the virtual test-bed modelling environment. This is a software package which is being developed with Office of Naval Research (ONR) funding.

In addition to researching power sources, CERDEC has a group investigating the reduction of power consumption. The simplest way of reducing power is to shut down systems when they are not in use. However, this is not always applicable to the military since, in many cases, there is a significant delay before systems come back on-line and this may be unacceptable to a soldier.

Another important issue is one of power conversion, where there is a great need to understand the complete system. There have been cases where equipment has contained numerous DC-DC converters due to continuous evolution, whereas if the total system were reinvestigated, a single converter would do the job with significant efficiency savings.

Ultracapacitors are also under investigation for some applications. A Zn-air battery-ultracapacitor hybrid is under consideration to power Javelin, a portable anti-tank weapon. Ultracapacitors are also used for laser designators and satellite burst communication systems. The leakage currents of ultracapacitors have reduced dramatically, possibly down as low as microamps. It might therefore be possible to keep these ultracapacitors topped-up by using a small Zn-air, Li-ion or PV system.

11.2.4 NAVSEA (Naval Sea Systems Command) – NSWC (Naval Surface Warfare Center) Carderock Division, West Bethesda, MD

The organisation of NAVSEA's Carderock Division, and funding for RD&D on EES, are described in Section 12.2.2.

The navy has fewer constraints on the number of battery types it can use. The US Army is aiming to reduce the number of battery types it uses to around 20, whereas the US Navy will accept a larger number of battery types since it has more varied applications and a different logistic chain.

Power source requirements range from microwatts to megawatts. The US Navy uses batteries from small button cells of 0.01 Ah capacity to large 10,000 Ah special batteries.

Li-ion batteries are used throughout the US Navy for applications such as mines, electronic and acoustic decoys, and communication systems. Ideally, the Navy would like to avoid lithium batteries from a safety standpoint, but in many cases they are accepted because of their performance. For example, Li-ion batteries are being tested for ASDVs (advanced swimmer delivery vehicles). However, the US Navy does not see large-scale lithium batteries as a power source for submarines for some time yet. There is a great concern over safety and, in particular, 'cascading' – when one cell catches fire and affects surrounding cells. NAVSEA has seen examples of cascading during some of its Li-ion tests. Some systems use larger numbers of small 18650 Li-ion cells since, although not the smallest solution, this greatly increases the redundancy of the system.

One of the UUVs NAVSEA is currently developing is the size of a torpedo and stores 150 kWh of energy in lithium-thionyl chloride cells. It may consider moving to Li-S in the future. NAVSEA generally focuses on near- to mid-term solutions and so is monitoring Li-S developments but is not actively involved since it does not believe the technology is mature enough yet. 'Zebra' (Na-$NiCl_2$) batteries have also been investigated.

NAVSEA's key criteria for power sources are similar to those of other armed services, ie safety, size, weight, reliability, cost and the ability to operate at temperature extremes.

In addition to naval vessels, NAVSEA is also responsible for the development of power sources for the US Marines. Hence it is developing Zn-air batteries as high-energy primary systems. It is also considering alternative metal anodes such as lithium and aluminium to provide increases in specific energy. In addition to the 8180 Zn-air form factor, it has put Zn-air cells into standard SINCGARS radio batteries and built a hybrid Zn-air/Li-ion power source that was exhibited during the tour of laboratory facilities.

The Zn-air BA5590 option is available with or without a fan fitted. The fan variant has fewer holes in the case, and so greater control of air access can be achieved. Hence self-discharge can be slowed when the battery is not in use, or at low rates, by drawing less air through the system.

These Zn-air hybrid systems can provide double the power and double the energy of the standard Li-SO_2 BA5590. The Zn-air hybrid system can readily supply the typical 20 W load drawn by a SINCGARS radio. A Zn-air battery can also be designed to be refuelled by the addition of a cartridge of fresh zinc. Some redesign of the SINCGARS battery compartment will be needed before it can accept a Zn-air system since the battery compartment is currently sealed and so would prevent air access.

A large part of NAVSEA's work involves safety testing of batteries, and it has facilities such as large high-strength steel chambers capable of withstanding 150 psi to enable this. It was interesting to note that when a battery explodes it does so more like a rocket motor than TNT, ie with an overpressure and less of a shock wave.

Other active development efforts included asymmetric capacitors, ultracapacitors (different electrolytes), portable fuel cells, metal-air batteries, lithium rechargeable batteries, lithium primary batteries, LA batteries, and hybrid systems. Preliminary work on asymmetric capacitors was shown during the laboratory tour. These can be seen as intermediate in performance between batteries and ultracapacitors. It is believed that specific energies as high as 24 Wh/kg and specific powers of 18 kW/kg could be achieved in the future.

Nuclear isomers, such as Hf-178, were also briefly discussed as having potential as high-energy density power sources, but these are controversial and not yet well understood, and it will be a significant time in the future before they can provide practical devices.

The Ship Service Fuel Cell Program is investigating the reformation of naval logistic fuel and its use in two types of 500 kW fuel cell – PEM and molten carbonate fuel cell (MCFC). This activity is managed by a different site located in Philadelphia, and so wasn't discussed in detail at this meeting.

There are no international collaborations at Carderock, but NAVSEA Philadelphia has just initiated a programme of Foreign Competitive Tender on fuel cells for UUVs.

11.2.5 DARPA (Defense Advanced Research Projects Agency), Washington, DC

DARPA's remit, structure and research budgets are described in Section 12.2.4.

The Palm Power Program, a large programme managed by DARPA which addresses the issues of soldier-portable power, is described below.

Palm Power Program

The US armed forces have a pressing need for lighter and smaller power sources for soldier, robotic and other applications. Batteries are presently used for these systems, and whilst these have many desirable features (low acoustic and thermal signatures, and air-independent operation), the quantity of energy stored is not sufficient to meet the needs of future missions at an acceptable weight. Many improvements to batteries are being made, and future advances are foreseen. However, it is still expected that there may be a tenfold shortfall in energy if batteries alone are used in the future.

Small energy-conversion devices, which convert high-energy content fuels to electricity, are needed to address this shortfall. The Palm Power Program is a technology development initiative that aims to advance the technology as far as possible by demonstrating new approaches that will ultimately lead to complete system demonstrations. It is not intended to develop a specific system that meets existing requirements by using off-the-shelf technology.

Conventional designs or off-the-shelf materials and components are unlikely to meet the challenging specific energy targets of interest to DARPA. Innovative approaches that include highly integrated materials and novel fabrication methods are required to meet the goals of the Palm Power Program. The military environment and thermal and acoustic signatures will be addressed in addition to system issues such as start-up, shutdown and load-following.

Easily handled and safe liquid fuels are preferred. JP-8 is the fuel of choice; however, other high energy content fuels, including, but not limited to, desulphurised JP-8, butane, methanol and ammonia will be considered, provided that they meet the Palm Power Program goals.

Projects that develop the science and technology (S&T) base that supports the Palm Power Program objectives are funded in Phase I. Important S&T topics include, but are not limited to: catalysis, combustion, advanced materials for thermal conductivity and insulation, thermal management and integration, multifunctional materials, compact integrated fuel processors, novel fabrication/materials processing methods, thermally integrated cascading systems, microchemical reactors, and integrated MEMS components. The outcomes of these projects should show an impact at system level.

The Palm Power Program aims to develop and demonstrate technology leading to the field demonstration of novel energy conversion devices at the 20 W average power level at 12 V DC. This power level was selected because many applications of interest require around 20 W, and it is expected that scaling-up to higher power levels (eg 50-500 W) will be straightforward if the 20 W goals are achieved. While it is expected that the larger systems will be of interest to DoD and commercial customers, DARPA does not plan to develop them under this programme. At the conclusion of the programme, DARPA expects to have field tested several energy conversion systems under realistic military conditions, and determined their relative merits based on performance and logistics impact.

To achieve these objectives, the Palm Power Program intends to develop complete, packaged, turnkey systems. This will require extensive development at the material, component, and system levels.

Three ‘mission scenarios’ have been selected to establish clear, quantitative goals for the programme. Assuming an average power level of 20 W, the mission lengths and minimum specific energy goals are as follows:

- Scenario 1: three-hour mission – 1,000 Wh/kg
- Scenario 2: three-day mission – 2,000 Wh/kg
- Scenario 3: ten-day mission – 3,000 Wh/kg

These specific energies include the complete system and fuel. Typical missions for these categories are: (1) a three-hour micro-air-vehicle reconnaissance mission, (2) a three-day Land Warrior mission, and (3) a ten-day special operations reconnaissance mission, respectively. These are examples only, and there will be other applications for the technologies developed. Systems should be as compact as possible because the energy sources will be carried by soldiers or integrated into small robotic systems. It may be desirable to operate the system while it is being carried; however, this is not a requirement for this programme.

The specific goals of the Palm Power Program, which is now in its last year, are illustrated in Exhibit 11.4. The most promising technologies will be taken to prototypes.

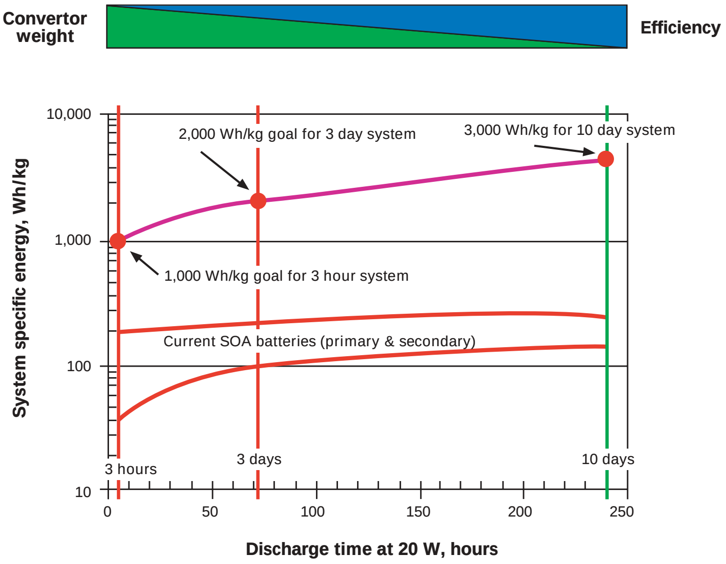

Exhibit 11.4 Palm Power Program goals[17]

11.2.6 ARL (Army Research Laboratory), Adelphi, MD

The broad activities of ARL, together with associated research budgets, are presented in Section 12.2.1.

It is expected that in the future the US military will want to use rechargeable batteries wherever possible. There is therefore pressure to focus research on secondary battery chemistries and not primary chemistries. However, the US foot-soldier currently uses mostly primary batteries during operations, and the change from this to secondary battery systems will involve significant logistics changes.

Most combat vehicles are already fully laden during conflict, and hence there may be a problem adding battery chargers to the already exhaustive list of equipment to be carried. It was noted that if trying to add extra equipment to a fully laden vehicle, something will need to be left behind in its place. This problem could be solved in the future by TARDEC’s aim that future combat vehicles will be HEVs with exportable power and built-in battery charging capability.

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[17] B Nowak. *Presentation at Palm Power Teaming Workshop,* Ft Lauderdale, FL, 14-15 November 2000: www.darpa.mil/dso/thrust/matdev/palmpower/presentations/nowak.pdf

ARL has previously funded some work into carbon-air cells, and although not currently active in this area, it believes the technology might have some benefit as a battery charger or range extender to secondary batteries. ARL expressed interest in carbon-air research being undertaken by DSTL in the UK.

As regards fuel cell systems, ARL considers that such systems will be used as advanced soldier-portable power sources and as APUs; it does not see a role for fuel cells in vehicle propulsion. ARL is interested in the reformation of sulphur-rich fuels for applications such as APUs. ARL believes it does not have the funding to do everything, and so tries to leverage where possible. It tries to use work funded by DOE where possible, but since DOE has no interest in S-rich fuels, and has moved away from the concept of on-board reforming, it is left for ARL and other DoD organisations to investigate this issue.

Under the Collaborative Technology Alliances (CTA) Program administered by ARL (see 12.2.1), the Power and Energy CTA aims to ‘advance fundamental sciences and understanding of efficient lightweight compact power and propulsion technologies needed for the individual soldier, fuel-efficient vehicles and robotic platforms of the future Army Objective Force’.

This CTA, which involve nine companies and 15 universities, is currently focused on three technical areas:

- Portable, compact power sources (non-electrochemical) – to develop enabling technologies for revolutionary, non-electrochemical soldier-power sources, with 10-times greater energy density than current batteries and capable of meeting the power and energy requirements of the soldier
- Fuel cells and fuel reformation – develop enabling technologies for soldier portable fuel cell systems, including fuel processing for hydrogen generation. Provide enabling technologies for logistics fuel reformation and fuel cells for vehicle propulsion and auxiliary power
- Hybrid electric propulsion and power – develop enabling technologies supporting efficient, compact, lightweight energy conversion and electric power conversion and conditioning for Future Combat Systems (FCS) and robotic platforms

CTA researchers participate in many key defence programmes such as FCS, Objective Force Warrior (OFW), Warfighter Information Network – Tactical (WIN-T), and Adaptive Joint Communications, Intelligence, Surveillance and Reconnaissance (CISR) Node (AJCN). Furthermore, each CTA member provides world-class laboratory facilities and test-beds for use by ARL and other CTA members.

In addition to work in the USA, ARL has a European office, and can manage and fund collaborative European programmes via this organisation. In the past, the majority of work has been with UK academic institutions due to the close relationship between the armed forces of the two countries.

11.3 Future developments

The provision of electrical energy has been recognised as a significant challenge by the US military. All of the military organisations visited had significant efforts under way in this area. It is recognised that one of the biggest challenges is the provision of portable power to dismounted soldiers. Much research is under way to address this problem, and this includes not only advanced batteries such as Zn-air, but also other power sources such as fuel cells and even small Stirling engines.

In addition to the military establishments, the Global Watch Mission team visited two small battery companies – Sion Power Corp and PolyPlus Battery Co – that were developing batteries which would be of interest to the US military for soldier power. Both of these developments involve lithium chemistry – not surprising since lithium is the metal with the highest specific capacity.

Sion Power's Li-S rechargeable battery technology is of interest due to the high specific energies claimed for the system and the prospects for lower production costs compared to Li-ion batteries. Already achieving 350 Wh/kg, Sion Power is predicting specific energies of 450 Wh/kg in the near future by simple improvements, and is targeting 600 Wh/kg in the longer term. The technology is not yet commercialised, and a number of issues remain to be solved before the batteries could become widely adopted. This technology is covered in more detail in Section 4.2.3.

PolyPlus has developed a way of protecting lithium such that it can be stabilised to water. A process has been developed which allows a coating of a lithium conducting glass to be placed on the surface of a lithium sputtered coating or lithium foil. This coating now enables a number of lithium metal battery technologies which were previously difficult or impossible to achieve because of the corrosion currents of lithium with water.

The two main chemistries being focused on by PolyPlus are Li-air for land applications and Li-water for marine applications. It is claimed that optimised Li-air cells will be capable of providing specific energies of 1,000 Wh/kg. It is initially envisaged that these will be primary cells but it is expected that the technology could be adapted to secondary cells with little or no loss in capacity. The Li-air technology is at a much earlier stage of development than the Sion Power Li-S battery, and PolyPlus estimates that it may be another 3-4 years before it has a battery pack available at a sufficient level of development for assessment by the military. This technology is covered in more detail in Section 4.2.6.

PolyPlus has also investigated Li-S chemistry, again utilising its coated lithium anodes. It is believed that this technology might be applicable to both portable and vehicle applications. The vehicle work is being supported by the DOE as a potentially cheap alternative battery chemistry for EV and HEV applications.

The graph in Exhibit 11.5 highlights the potential for future electrochemical power sources. The values and timelines are estimates and will depend greatly on solving technical challenges with the new systems and the level of funding devoted to their development.

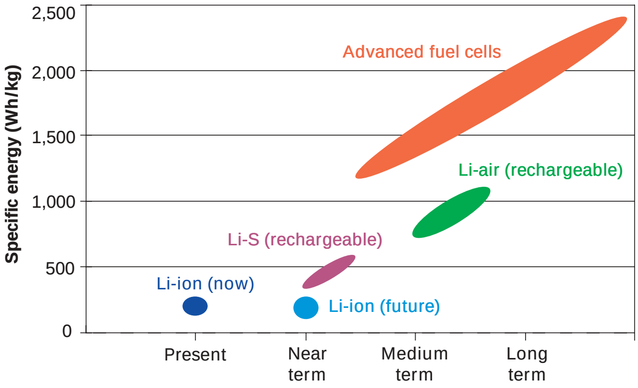

Exhibit 11.5 Illustrative specific energies of future power sources (speculative timeline) (source: DARPA)

Li-ion will show only marginal improvements in capacity over time since it is a mature technology. Estimates of capacity improvements of 10-25% over the next decade or so are common. Major improvements in specific energy are unlikely, and improvements are likely in cost reduction and other performance attributes. Li-S has already been demonstrated at 350 Wh/kg in packaged prismatic cells, and the manufacturer has estimated that 600 Wh/kg may be possible in the future. Rechargeable Li-air cells are still at an early stage of development but have the potential for specific energies of 1,000 Wh/kg. It is more difficult to estimate the specific energy of future fuel cells since much depends upon the scale and run-time, but DARPA is estimating that future optimised fuel cell systems may even approach 3,000 Wh/kg for low-power, long-duration missions.

11.4 Markets and opportunities

The US military is significantly larger than that of the UK, and hence the market for power sources is proportionally larger. It is difficult to quantify the size of the US military battery market since it is spread across numerous organisations. However, an estimate of $250 million annually and growing was given for batteries for portable military equipment in 2002[18].

There are a number of areas where improved ES systems are desperately needed and it would be possible for a company which could provide a solution to these energy problems to gain a foothold in this large market.

The greatest need is for a rechargeable soldier-portable power source with a high specific energy. Ideally, specific energies in excess of 700 Wh/kg would be desired, to enable a 20 W power source to operate for 72 hours and weigh less than 2 kg. This would be a difficult target for a rechargeable battery system to meet, which is why much research is under way on fuel cells and heat engines. However, it is likely that a rechargeable battery which could meet all military environmental and safety criteria but which could offer significant improvements over today's Li-ion technology would still be looked upon favourably, even if it could not achieve 700 Wh/kg.

The other growing market for energy stores for the military is for vehicle-based ES to provide exportable power. The need for exportable power from vehicles is clearly recognised, with TARDEC predicting that all of its future combat vehicles and up to 10% of its tactical vehicles will have some form of exportable power. This is in part due to the desire to replace many of the primary batteries currently in use with rechargeable secondary batteries. Once again, a battery system would be in competition with fuel cell APUs, such as those that may operate using reformed logistic fuel, or regenerative fuel cells.

In addition to the markets discussed above, there is also opportunity to collaborate with US military organisations on R&D programmes. A number of organisations such as the ARL and ONR have a European office based in London and whose role is to coordinate collaborations with the UK and the rest of Europe. Traditionally, such collaborations have been with UK academia due to the close links between the USA and the UK.

There is also potential for UK companies to have their products evaluated by US military establishments under Foreign Competitive Test and Evaluation Programs such as those operated by CERDEC and other organisations.

11.5 Key messages

- Electrochemical power sources are a significant problem for the US military, and improved electrochemical power sources are needed. This need is being addressed by a number of DoD research establishments across the USA

- The greatest need is for dismounted soldier electronics for programmes such as Land Warrior and Future Force Warrior

- Advanced battery chemistries are being investigated, but other alternatives such as fuel cells and small Stirling engines are

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[18] *Battery & EV Technology,* January 2002

also being examined. Of the alternatives, it is only battery systems that are independent of air, and so it is likely that future power sources may be hybrids containing batteries and another power source

- No ideal solution to the problem has been found, and therefore there are opportunities for UK companies and research organisations to work with the USA to find solutions to the provision of power to the dismounted soldier. This is not only a problem for the US military, but for the military of all developed countries as they aim to increase the electronic capabilities of their future soldiers

12 FEDERAL AND STATE SUPPORT

The research, development, demonstration and deployment of electrochemical energy storage (EES) systems for a range of market applications has been greatly assisted in the USA through support activities of both the US federal government and the governments of a number of States.

Federal government support for EES has principally been through various offices of the US Department of Energy (DOE) and through the various armed forces (individually and jointly) under the US Department of Defense (DoD).

While a number of individual States have a growing interest in EES (for a number of different reasons), active State government support has been mainly focused in California and New York State, both of which have established joint funding programmes with DOE to develop and demonstrate ES devices (primarily electrochemical technologies) at a range of scales and in a range of applications.

This chapter examines the main research, development and demonstration (RD&D) activities concerning EES technologies supported by DOE, DoD, the California Energy Commission (CEC) and the New York State Energy Research and Development Authority (NYSERDA). While detailed descriptions of specific technologies, applications and specific projects/installations occur elsewhere in this report, this chapter describes the various drivers, programmes, budgets, etc for each of these federal/State initiatives.

Other federal agencies (eg Department of Transportation, NASA, etc) and other States (eg Connecticut, Michigan, etc) are also undertaking some activities in EES. Furthermore, some interagency cooperative activity is taking place. These activities were not covered by the mission, and this chapter should not be viewed as an exhaustive review of federal and State activities and support.

12.1 US Department of Energy (DOE)

www.energy.gov

The overarching mission of DOE is to advance the national, economic and energy security of the USA. In support of this, it has four strategic goals:

- Defence – to protect national security by applying advanced science and nuclear technology
- Energy – to protect national and economic security by promoting a diverse supply and delivery of reliable, affordable and environmentally sound energy

- Science – to protect national and economic security by providing world-class scientific research capacity and advancing scientific knowledge
- Environment – to protect the environment by providing a responsible resolution to the environmental legacy of the Cold War and by providing for the permanent disposal of high-level radioactive waste

Clearly, ES is highly pertinent to the first three of these goals, and DOE has a strong remit to promote scientific and technological innovation in this area.

Owing to the diverse applications of ES, several parts of DOE have an interest in ES, including electrochemical devices. The key areas of activity on these technologies come under the auspices of the Office of Electric Transmission and Distribution (OETD) – particularly the Energy Storage Systems Program (stationary power applications) – and the Office of Energy Efficiency and Renewable Energy (EERE) – particularly the FreedomCAR Partnership (transport applications). EERE also has interests in distributed energy resources/systems (ie integrated distributed energy generation/storage systems) and issues associated with intermittent renewable energy (RE) sources (eg wind energy and photovoltaic (PV) solar energy resources): however, RD&D addressing these issues and applications are covered under the activities of OETD to avoid duplication of effort. Sandia National Laboratories (SNL) in Albuquerque, New Mexico (one of the 12 major national laboratories of DOE), undertakes an impressive programme of activities at its Distributed Energy Test Laboratory (DETL), funded by a broad range of customers including EERE and OETD.

12.1.1 Office of Electric Transmission and Distribution (OETD)

www.electricity.doe.gov

The electricity blackout of 14 August 2003 caused a major re-evaluation of the nation's priorities for electricity transmission, distribution and storage. Eight States and one Canadian Province were affected by the incident, which involved more than 250 power plants. Around 50 million people were left without power (many for several days), three deaths were attributed to the blackouts, and an estimated $4.5-10 billion (£2.4-5.3 billion) of economic activity was lost. However, this was not a one-off, following on from major incidents in Texas the same year, Northern California in 2001 and 2000, Detroit in 2000 and New York, New Orleans, Delaware, Atlanta and Chicago in 1999. All in all, electricity blackouts and brownouts are estimated to cost $25-188 billion (£13-99 billion) annually in lost economic activity.

As a result of the 2003 outages, a US-Canada Power Outage Task Force was established and four 'national (energy) reliability challenges' identified:

- Prevention – including the application of ES technologies
- Detection
- Response (ie a proper 'toolkit' for any contingency) – including ES (MW and MVAR-scale support)
- Modernisation (ie 'next generation' grid technologies) – including ES

The modernisation and expansion of the US electricity delivery system to ensure more reliable and robust electricity supply has received considerable impetus following President Bush's comment that: '*We want the most modern electricity grid for our people… we need more investment; we need research and development….*'

As a result, the Energy Storage Systems Program, along with other R&D programmes addressing other key areas of transmission and distribution (T&D) technology, is likely to gain increasing priority in 2005.

Energy Storage Systems Program (R&D)

www.sandia.gov/ess
www.electricity.doe.gov/program/electric_rd_estorage

This programme (managed for DOE by SNL, visited during the course of the mission) aims to develop advanced, large-scale (hundreds of kW to MW scale), stationary electricity storage devices for modernising the expanding electricity supply infrastructure in the USA. Such devices will improve the quality, reliability, flexibility and cost effectiveness of the existing system, as well as facilitating the use of distributed energy resources. The programme is undertaken in partnership with industry (developers and users) and individual States, and covers electrochemical storage, electromechanical storage (eg flywheel systems), pumped storage, CAES and SMES systems.

The specific goals of the programme are to:

- **Develop** integrated ES systems (batteries, flywheels, ultracapacitors, etc)
- **Improve** controls, etc
- **Analyse** and compare different systems relevant for different applications
- **Secure** participation from industry and academe

The scope of the perceived applications for ES within the programme is illustrated in Exhibit 12.1

Power ⟶ Energy

	seconds	minutes-hours	diurnal
Load	Power quality, digital reliability	Distributed energy resource – support for load-following	Peak shaving to avoid demand charges
Grid	Voltage support, transients	‘Dispatchability’ for renewable energy, village power	Transmission congestion mitigation, arbitrage

Exhibit 12.1 Perceived applications for ES in DOE’s Energy Storage Systems Program

Federal funding of up to $4-10 million (£2.1-5.3 million) has been made available annually since the programme started in 1992, with recent budgets of $5.2 million (2002), $4.5 million (2003), $9 million (2004 but with $7.1 million ‘earmarked’ by Congress for particular projects), and $10 million (2005, but with $8 million earmarked). The emphasis is now on demonstration projects, particularly with industry and State partners to ensure linkage with local and regional issues. Of this total budget, around $7-8 million/year (~£3.7-4.2 million/year) is directed at EES.

Examples of major EES projects supported under the programme include:

- **TEPCO/NGK** Na-S battery system at an AEP site – the first commercial use of Na-S batteries in the USA. The 100 kW, 7.2 h/600 kW, 30 s battery can be used for peak-shaving (70 kW for 12 h) and power quality control (300 kW for 1 min). DOE is monitoring the project remotely

- **Saft/SatCon** Li-ion battery system at a Southern Company site – this 100 kW, 1 min power quality system is designed to support/stabilise a grid-connected microturbine and provide UPS. Initial tests produced 100 kW for 3 min. The system has now been tested for over 1,000 h. A second system is to be tested at AEP

- **ElectroEnergy/First Energy Ni-MH** battery system – the bipolar flexible wafer technology used in these 3 kW batteries was developed with DOE funding and will be tested in comparison with ultracapacitors. Their high energy density will encourage use for peak-shaving at substations, and area control signal following

- US Coast Guard – alternative configuration ('ACONF') distributed energy (eg PV-generator hybrid) 100 kW systems at 24 National Distress System locations, with a battery management system that finishes charging one battery string from another string. This approach reduces generator run-times, maximises battery life, and maximises the value of the PV energy

- Working with EPRI to produce the 'Handbook of Energy Storage for Transmission and Distribution Applications', published in December 2003 and currently being updated

A programme of support activity is undertaken at SNL's DETL (see Section 12.1.3).

The Energy Storage Systems Program is also the means by which DOE provides financial and technical contributions to the joint ES initiatives with CEC and NYSERDA (see Section 12.5).

12.1.2 Office of Energy Efficiency and Renewable Energy (EERE)

www.eere.energy.gov

The USA uses over 98.1 'Quads' (quadrillion – 10^{15} – BTU), or about 103.5 EJ of energy each year, and this is projected to grow to 130 Quads/year by 2020. Just under 40% of current primary energy is in the form of petroleum, and this is of critical concern from an energy security standpoint, since more than 60% of the oil consumed currently in the USA is imported, with this figure likely to rise to around 70% by 2030. The transportation sector accounts for nearly two-thirds of the annual consumption, of which about 80% is used to power highway vehicles.

In addition to the energy security driver, the contribution of the transportation sector to emissions of greenhouse gases (GHGs – the USA produces nearly a quarter of the world's total GHG emissions) – and the associated impact on global climate change – as well as the impact on local air quality, has spurred DOE to focus considerable effort on this sector of the US economy.

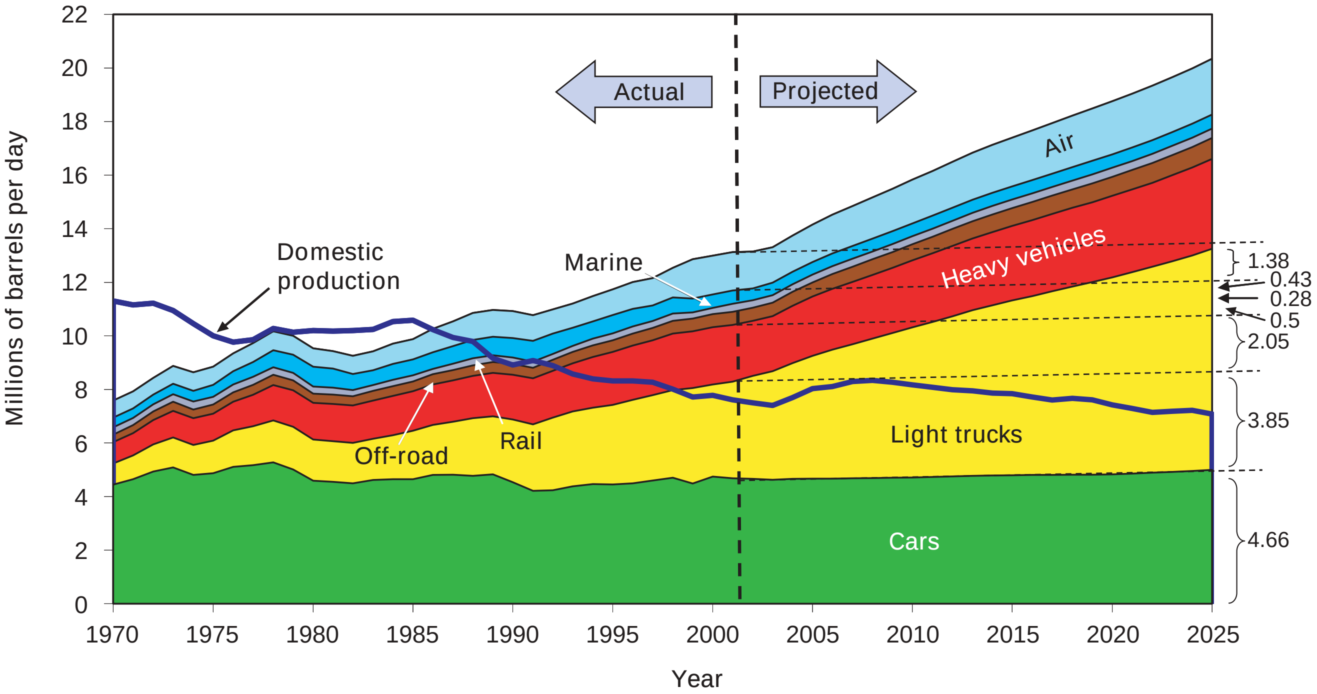

Exhibit 12.2 US transportation oil use to 2025 (source: DOE)

The importance of cars, heavy vehicles and, particularly, light trucks (including SUVs) on future US transportation oil use is illustrated in Exhibit 12.2.

The prospect of developing alternative vehicles for the expanding global market that achieve better fuel efficiency and lower emissions while offering performance, utility benefits and cost comparable to (or better than) internal combustion engine (ICE) vehicles is at the forefront of thinking of the US auto industry. Several hybrid electric vehicles (HEVs) have been introduced into the US market over the last 3-4 years from manufacturers such as Toyota, Honda and Ford, and several US auto manufacturers (notably General Motors and Ford) are committed to developing and marketing fuel cell vehicles (FCVs) and/or hybrid fuel cell vehicles (HFCVs) over the next 10-15 years. Work also continues to improve battery electric vehicles (EVs) for particular niche applications, eg ‘neighbourhood vehicles’. The challenge is for the USA to work towards energy independence and market leadership while maintaining consumer choice and mobility.

ES technologies, including batteries and ultracapacitors, are critical enabling technologies for the development of advanced, fuel-efficient, light- and heavy-duty vehicles. This is true no matter what the vehicle drive system comprises, ie advanced ICE vehicles, HEVs (‘mild’ or ‘power-assist’ systems), EVs, HFCVs or FCVs.

EERE funds a considerable amount of activity in smaller scale EES, particularly for applications in the transport sector (through the FreedomCAR Partnership and the 21st Century Truck Partnership).

As has already been described, EERE also manages activity in integrated distributed energy generation/storage systems (through various programmes including the Distributed Energy Program and the Solar Energy Program) and wider (and generally larger scale) ES issues associated with intermittent RE sources, eg wind energy: ES RD&D addressing these areas is undertaken through OETD’s Energy Storage Systems Program already described in Section 12.1.1

FreedomCAR and Vehicle Technologies Program

www.eere.energy.gov/vehiclesandfuels

The FreedomCAR (Cooperative Automotive Research) Partnership was launched in 2002, building on several previous programmes. The partners are DOE and the US Council for Automotive Research (USCAR), a joint venture formed by Ford, General Motors and DaimlerChrysler. Activities focus on funding collaborative, precompetitive, high-reward/high-risk research that promises improvements in critical components needed for more fuel efficient, lower emission and affordable passenger cars and light trucks. This includes work on manufacturability and HEVs and provides ongoing guidance and expertise to DOE’s ES activity. R&D activities are being funded at national laboratories (including NREL in Golden, Colorado – visited as part of this mission), universities and other research institutes, as well as at traditional and non-traditional automotive industry suppliers.

The 21st Century Truck Partnership was launched in 2000 and involves cooperative effort among key members of the heavy vehicle industry, truck manufacturers, hybrid propulsion developers, engine manufacturers and several federal agencies. The aims are similar to the FreedomCAR Partnership, but focused on enhancing technologies for heavy vehicles to improve safety, efficiency and environmental performance. Ultimately, the Partnership seeks to develop trucks and buses that use sustainable and self-sufficient energy sources, thereby enhancing the industry’s competitiveness.

In 2002, the FreedomCAR and Vehicle Technologies (FCVT) Program was formed by bringing these two Partnerships together with various other activities in other EERE programmes. The FCVT Program aims to expand its emphasis on EES and materials technologies.

EES RD&D effort within the FCVT Program is addressing innovative batteries for a wide range of vehicle applications, including HEVs, EVs, potential 42 V vehicular systems and FCVs/HFCVs. These activities are coordinated by the US Advanced Battery Consortium (USABC), a partnership representing the automotive industry participants within USCAR and DOE (see Section 13.2.4).

The current effort on EES comprises the following three activity programme areas:

- Battery Technology Development – 'Developers Program' (primarily through USABC)

  This area maintains a balance between R&D projects that aim to directly aid the introduction of advanced EES technologies into the automotive marketplace. Work focuses on EES systems, especially rechargeable batteries. Researchers maintain a balanced portfolio of R&D projects aimed at overcoming the barriers hindering the commercial viability of advanced EES systems in HEVs. Work focuses on four areas:

  - Full-system development for EV and HEV applications: developing and evaluating a cost-optimised, liquid-cooled Ni-MH monoblock module for HEVs; addressing the issues that reduce the useful life of Li-ion batteries in EVs; cost reduction of Li-ion HEV modules; developing an advanced Li-S battery system that has the potential of meeting all EV targets including cost; ultracapacitors for HEVs

  - Technology assessment: 12-month assessments to independently validate newly emerging technologies including Li-ion gel technology, spinel-based chemistry, and a new $LiFePO_4$ cathode active material

  - Benchmark testing: working with national laboratories to independently test hardware against manufacturers' specifications and the most applicable technical targets, eg Li-ion/Mn (spinel) chemistries against HEV/EV targets

  - Small Business Innovation Research (SBIR) Program: this programme (which runs to 2008) is designed to stimulate technological innovation, strengthen technological competitiveness of small businesses and use them to meet federal R&D needs. For several years, SBIR contracts have provided valuable support to EV and HEV battery development activity. Approximately $4 million/year (~£2.1 million/year) is focused on the development of new battery materials and components

- Applied Battery Research Program (primarily accomplished through five of DOE's national laboratories – see Section 12.1.4)

  Several types of batteries have been investigated for use in EVs and HEVs, including Li-Al-Fe sulphide, Ni-MH, Li-ion and Li-ion-polymer. Li-ion systems come closest to meeting all of the technical energy and power requirements, but they face four barriers: calendar life, low-temperature performance, abuse tolerance and cost. This activity focuses on addressing these cross-cutting barriers facing Li-ion systems and ensuring technology transfer to US automotive and battery manufacturers. Work focuses on four research areas:

  - Battery system development and electrochemical diagnostics

  - Battery testing and electrolyte development

  - Spectroscopy and microscopy diagnostics, including X-ray diagnostics

  - Abuse evaluation, accelerated life test protocol development and statistical analysis

- Long-term Exploratory Research Program (primarily accomplished through five national laboratories)

  This focused fundamental research programme addresses problems of chemical instabilities that impede the development of advanced batteries in order to help to understand why systems fail, develop models that predict system failure and permit system optimisation, and investigate new and promising materials. Work focuses on six research areas:

  - Advanced cell chemistry: to investigate the failure and degradation modes in three 'baseline' systems (rechargeable Li cell chemistries), self-actuating overcharge protection mechanisms, synthesise and evaluate alternative electrode materials and support cell development

  - Improved or non-carbonaceous anodes: to overcome key problems with carbon-based anodes used in commercial Li-ion batteries (ie poor safety characteristics and short lifetimes) either improved anode structures or non-carbonaceous anodes need to be developed. Low-cost metal alloys with acceptable capacity, rate, cyclability and calendar life are being investigated

  - New electrolytes: research into the performance of polymer electrolytes, ie transport properties of the electrolyte as a function of polymer and salt structure, polymer structural changes with temperature, and interactions at the electrode/electrolyte interface related to transport and chemical/mechanical stability

  - Novel cathode materials: the cost and environmental limitations of cobalt- and vanadium-based materials used in current lithium batteries make the identification and development of novel cathodes a critical matter. The focus is currently on high-rate and stable MnO_2 cathodes, although rapid capacity loss ('fade') needs to be better understood

  - Advanced diagnostics and analytical methods: these are essential for investigating life-limiting and performance-limiting processes in batteries. Post-test analyses, spectroscopic and microscopic techniques are used to investigate morphology, structure and compositional changes of electrode materials

  - Phenomenological modelling: sophisticated modelling assists in understanding the complex interactions and failure mechanisms of lithium battery components and thermal 'runaway'

The FCVT Program had a total federal budget of $176 million (~£93 million) in FY2004, with the expectation of a similar budget in FY2005. Of this total FY2004 budget, $23.4 million (~£12.3 million) was allocated to ES (all electrochemical technologies for this application), of which 51% was for the 'Developers Program'. Judging from Congressional Marks, the FY2005 allocation to EES will rise slightly to $23.7 million (~£12.5 million), with 47% going to the Developers Program.

12.1.3 Sandia National Laboratories (SNL)

www.sandia.gov/ess

SNL, established in 1949 as an offshoot of Los Alamos, is one of the 12 major national laboratories of DOE and is operated under contract by Lockheed Martin. The primary mission of SNL is in the area of nuclear weapons (stewardship of stockpiles, non-proliferation and assessments), but as with all such labs, SNL has a broader mission in energy science and engineering to meet energy security needs: in SNL's case, this is focused on energy infrastructure and assurance.

The overall budget of SNL in FY2003 was $2.075 billion (~£1.09 billion), involving around 10,250 employees (7,000 at the Albuquerque, New Mexico site and the balance at sites in California, Nevada, Hawaii, Texas and Washington, DC).

SNL, through its Power Sources Engineering and Development Department, has a broad base of EES expertise focusing on integrated storage systems. Such systems are required to operate in varying environments and electrical conditions – hence requiring a broad range of technologies for a range of applications, eg thermally-activated primary batteries (such as Li(Si)-FeS_2), active and reserve ambient-temperature primary batteries, a wide range of secondary (rechargeable) batteries, ultracapacitors and other power sources (such as radioisotopic thermoelectric generators (RTGs)) for specific military, aerospace and commercial applications. Commercial applications range from advanced batteries for EVs and telemetry applications to large battery systems used by electric utilities for load-levelling and other applications.

A major focus of activity on ES at SNL is the management of the OETD Energy Storage Systems Program described in Section 12.1.1 above. In addition to managing this major DOE programme, SNL also manages the Mexico Renewable Energy Program. This programme (see www.re.sandia.gov), sponsored by DOE and USAID, works with partnership organisations to implement pilot and demonstration technology projects and stimulate replication of RE installations. In the 10 years that the programme has been running, more than 400 pilot/demonstration plants have been installed leading to more than 3,500 replication installations. Technical assistance, training and education have supported the hardware projects, building capacity in Mexico. The RE technologies supported (mainly PV and wind systems) have been used in a wide range of applications including refrigeration, ice-making, irrigation, livestock and ranch potable water supply, drip irrigation, electric fences, milk cooling, greenhouses and water purification. EES has been a key enabling technology for these projects, with technologies from LA batteries to Ni-MH batteries being applied.

In addition to programme management activities, SNL acts as an independent test facility for both industry and government, with facilities to test and evaluate electrochemical power sources and distributed energy resources. A key facility in this respect is the Distributed Energy Test Laboratory (DETL).

The activities undertaken at DETL are for a range of customers including EERE's Solar Energy Program (which accounts for about 60% of the income), OETD's ESS Program, DoD, CEC and utilities. DETL is a fully-instrumented, configurable, controlled, utility interconnected test-bed for study of a variety of issues that might be raised by utilities concerning the interactions of multiple, distributed sources of various technologies (including PV, microturbines and fuel cells). Efficiency, power quality and control (for grid-tied and stand-alone) systems can be tested, with a SCADA facility to allow linkage to remote distributed energy sites and customers.

Distributed energy equipment available at DETL includes two 30 kW PV arrays with mono-crystalline, poly-crystalline and thin-film PV modules; a 30 kW hybrid PV-generator-battery system; a Kohler gas-fired power system; 28 kW Capstone and 75 kW Ingersoll-Rand microturbines; a 5 kW PlugPower fuel cell; a PV simulator; and various test stands.

12.1.4 Other national laboratories

Apart from SNL (see Section 12.1.3 above) and NREL (see Section 12.1.2), a number of DOE’s other national laboratories are also directly involved in supporting OETD and/or EERE in electrochemical energy research. These include:

- Argonne National Laboratory (ANL)
- Brookhaven National Laboratory (BNL)
- Idaho National Engineering and Environmental Laboratory (INEEL)
- Lawrence Berkeley National Laboratory (LBNL)

12.2 US Department of Defense (DoD)

www.defenselink.mil

DoD was created in 1949 and brought together under one department the US Army, US Navy, US Air Force, US Marine Corps and US Coast Guard. With around 1.4 million men and women on active duty, and about 654,000 civilian personnel, the US armed forces are the nation's largest employer.

DoD manages a vast and comprehensive inventory of installations, facilities, vehicles, ships, aircraft and other equipment. In terms of installations alone, more than 600,000 individual buildings and structures are located at more than 6,000 different locations or sites. Clearly, the resulting requirements for reliable and high quality stationary power are great, with equally demanding requirements for transportation and mobile/portable applications. It is not surprising, therefore, that there is considerable need for more advanced power source and ES technologies across all parts of the armed forces.

A wide range of RD&D activities in the area of EES are undertaken in the Army, Navy and Air Force, but not in the Marine Corps or the Coast Guard.

The sections below broadly describe the different organisations within the three armed services that are active in researching and developing EES technologies. However, the RD&D programmes, projects and activities of all of these organisations form part of Chapter 11 of this report, as they generally relate directly and only to the military applications of EES technologies.

12.2.1 US Army

RDECOM
www.rdecom.army.mil

The main focal point for ES work within the US Army is the Research, Development and Engineering Command (RDECOM), part of the Material Command which has overall responsibility for the acquisition and supply of equipment for the Army.

TACOM, TARDEC and NAC
www.tacom.army.mil
www.tacom.army.mil/tardec
www.tacom.army.mil/tardec/nac

Within RDECOM, the Tank-Automotive Command (TACOM) has responsibility for the acquisition, supply and deployment of military vehicles and associated ancillary equipment. It is also responsible for buying R&D to support combat vehicles for the US Army. As such, TACOM has considerable interest in ES as part of a larger operational platform (eg vehicles, tanks, etc), where size and weight issues are less significant.

RD&D activity in this area is undertaken by the Tank-Automotive Research, Development and Engineering Center (TARDEC) and its National Automotive Center (NAC), both based (along with TACOM) at the Detroit Arsenal at Warren, Michigan, and visited during the mission. Also located at Warren are two Program Executive Offices (PEOs) administering army-wide activity in combat systems and combat service support (eg trucks, boats, water purification, fuel, etc).

TARDEC's remit is to research, develop, engineer and integrate advanced drive, power and energy technology into military vehicles and on-board support equipment throughout the life cycle. Its programmes push the state-of-the-art in areas including power and energy systems, robotics, electric drive systems and embedded simulation to meet the mobility needs of the Army. This remit does not include dismounted power generation. Due to the current international situation, TARDEC's work has undergone some refocusing, with more effort being spent addressing immediate vehicle issues for the current conflict, in addition to developing future combat vehicles.

TARDEC has a staff of around 1,100, and the bulk of their work (~60%) is in support of TACOM and the PEOs. Around 80% of TARDEC's funding is contracted-out to industry and academia. Because of the nature of its work, TARDEC does not have many industrial partnerships, and the few that it has are with US companies.

TACOM and TARDEC expenditure on RD&D into EES has increased significantly in recent years, rising from $1.5 million in 2002 to $5.6 million in 2004 and $13.4 million (~£7.1 million) in 2005.

CECOM, CERCEC and PSCOE
www.monmouth.army.mil/cecom
www.monmouth.army.mil/cecom/rdec

Also within RDECOM, the Communications-Electronics Command (CECOM) has responsibility for the acquisition, supply and deployment of command and control electronics and communications equipment. As such, CECOM has considerable interest in man-portable EES systems for individual soldiers, where size and weight issues are critical.

RD&D activity in this area is undertaken by the Communications-Electronics Research, Development and Engineering Center (CERDEC) and its Power Sources Center of Excellence (PSCOE), both located at twin sites at Fort Monmouth, New Jersey (visited during the mission) and Fort Belvoir, Virginia.

CERDEC's remit is to research, develop and engineer non-vehicle integrated power sources for the army. While this has mainly focused to date on integrating near- and medium-term power source technologies (ie batteries and battery chargers) for the dismounted soldier (note that the average US soldier now carries approaching 100 W of power source), fuel cell and Stirling engine technologies have recently reached a sufficient state of maturity to warrant CERDEC's attention. CERDEC generally aims to take technologies from analytical studies and/or proof-of-concept through to system/subsystem model or prototype demonstration in relevant environments.

CERDEC has a staff of over 1000, with about 100 in the Army Power Division addressing power source requirements from 'soldier/sensor power' (1-100 W) to auxiliary power units (500 W to 10 kW). CERDEC supports basic and applied research at a number of US universities (Notre Dame, South Carolina and Connecticut), and also administers a $1 million (~£530,000) Foreign Comparative

Test Program to technically validate overseas technology: this has focused on fuel cell technology to date (including Intelligent Energy in the UK's 2 kW PEMFC), but is anticipated to be addressing battery technologies from Europe and Asia in the future.

CECOM and CERDEC expenditure on RD&D into EES is approximately $23 million/year (~£12.1 million/year). Of this, some $20 million/year is earmarked by Congress for particular projects.

ARO, ARL and ISN

www.aro.army.mil
www.arl.army.mil
www.mit.edu/isn

The Army Research Office (ARO) is responsible for procuring appropriate basic and applied research to underpin the US Army's technology needs.

The Army Research Laboratory (ARL) at Adelphi, Maryland (visited as part of the mission) is a part of ARO and scopes technologies emerging from industry and academia and performs preliminary research that then feeds into the various RDECOM centres such as TARDEC and CERDEC.

This activity includes administering the Collaborative Technology Alliances (CTA) Program, which acts as a vehicle for engaging industry and academia in collaborative research to solve military needs. Five CTAs were established in 2001 on the following topics:

- Advanced sensors
- Power and energy
- Advanced decision architectures
- Communications and networks
- Robotics

The projected value of each CTA is around $35 million (~£18.5 million) over five years or $20 million (£10.5 million) over three years. Each is managed by a senior ARL staff member. The CTA Program allows ARL to withhold up to 10% of the annual budget to fund external groups for innovative research. CTA researchers participate in many key defence programmes. Furthermore, CTA members provide world-class laboratory facilities and test-beds for the use of ARL and other CTA members. These facilities create tremendous leverage for the US Army's RD&D activities.

The Power and Energy CTA (with its objective to advance fundamental science and understanding of efficient, lightweight, compact power and propulsion technologies needed for the individual soldier, vehicles and robotic platforms) would seem to be the most relevant to ES technologies, although the technical areas under consideration currently exclude EES.

Also at the more fundamental research end of the spectrum, ARO – in collaboration with MIT and a number of industrial partners – has set up the Institute for Soldier Nanotechnologies (ISN), based at MIT in Cambridge, Massachusetts. ISN, which opened in 2003, has $100 million (~£53 million) of funding for its first five years, 50% of which was provided by ARO. The goal of ISN is to develop a 21st Century battlesuit that combines high-technology capabilities with light weight and comfort.

ARO's expenditure on RD&D into EES (including through activities at ARL and ISN) is around $5 million/year (~£2.6 million/year).

OnPoint Technologies

www.onpoint.us

The US Army, through its Army Venture Capital (VC) Initiative Program, established OnPoint Technologies in 2002 to develop 'better collaborative ties with young, small, growth-oriented companies that take risks and push innovation'. OnPoint will invest in or otherwise assist such companies developing innovative technologies of interest to the US Army, specifically within the technology areas of interest. The investment activity undertaken by OnPoint is expected to provide the US Army greater visibility into the technical development activities of companies that deal in areas of science and technology (S&T) of interest to the US Army and to accelerate the transition of new, or significantly improved, technologies.

OnPoint has a primary mission to facilitate finding and creating dual-use products – products addressing the needs of commercial markets that will also meet the needs of the individual soldier. As such, OnPoint's investments are strategic in nature, and hence it invests at any stage of a company's life cycle. Typical investment size ranges from $500,000 to $2 million (£260,000 to £1.05 million). The core investment area is mobile power and energy enabling technologies, such as generation technologies (eg fuel cells and microturbines), storage technologies (eg batteries and ultracapacitors), energy management technologies and software, controls, distribution technologies and energy use devices.

OnPoint's portfolio currently comprises the following companies addressing EES technologies:

- A123 Systems, Boston, Massachusetts – developer of advanced Li-ion based cells for rechargeable battery packs
- PowerGenix, San Diego, California – developer and seller of next-generation rechargeable batteries
- PowerPrecise, Fairfax Station, Virginia – fabless semiconductor company specialising in battery management devices
- Zinc Matrix Power, Santa Barbara, California – formed to develop high-performance rechargeable alkaline battery technology for commercial and military markets

To date, a total of some $37 million (~£19.5 million) of federal funding has been invested through OnPoint Technologies. Around $3-4 million/year has been invested in EES technologies.

12.2.2 US Navy

ONR
www.onr.navy.mil

The Office of Naval Research (ONR) coordinates, executes and promotes the S&T programmes of the US Navy and Marine Corps through schools, universities, government laboratories, and non-profit and for-profit organisations. It provides technical advice to the Chief of Naval Operations and the Secretary of the Navy and works with industry to improve technology manufacturing processes.

ONR does not undertake RD&D activity on EES technologies but funds NAVSEA (see below) to perform these functions and to provide advice to ONR.

NAVSEA and NSWC-Carderock
www.navsea.navy.mil
www.dt.navt.mil

The Naval Sea Systems Command (NAVSEA), the largest of the US Navy's five systems commands, is responsible for engineering, building and supporting the Navy's fleet of ships and combat systems. Accounting for nearly one-fifth of the US Navy's budget (~$20 billion, or ~£10.5 billion), NAVSEA manages more than 130 acquisition programmes, which are assigned to six affiliated Program Executive Offices (PEOs) and various Headquarters elements.

NAVSEA's remit covers the whole range of R&D from laboratory research through applied research to equipment optimisation and demonstration. In addition to the work for ONR on power sources for naval vessels, NAVSEA also performs work for the PEOs and the US Marine Corps.

NAVSEA's Carderock Division undertakes R&D, testing, evaluation, fleet support and in-service engineering activities for surface and underwater vessels. It operates from a number of sites including the Naval Surface Warfare Center (NSWC-Carderock) located at West Bethesda, Maryland (visited as part of the mission), the Naval Ship Systems Engineering Station (NAVSSES) in Philadelphia, Pennsylvania, and a large number of test and trials centres.

NSWC-Carderock has a Power and Protective Systems Branch which includes a Battery Technology Group that undertakes testing and evaluation work in the areas of EES and system safety. This work covers the range from micro- to megawatts ('sensor to sub').

The total US Navy expenditure on RD&D into EES is approximately $30 million/year (~£15.8 million/year).

12.2.3 US Air Force

AFRL and Wright Research Site
www.afrl.af.mil

The Air Force Research Laboratory (AFRL), headquartered in Arlington, Virginia, is responsible for planning and executing the US Air Force's entire S&T budget of nearly $1.7 billion (~£0.9 billion). This includes basic research, applied research and advanced technology development, and an additional $1.3 billion (~£0.7 billion) from AFRL customers. AFRL has a wide spectrum of laboratory facilities across the USA, and employs approximately 9,500 people. AFRL was not visited as part of this mission.

Activity on energy and propulsion systems (including EES) takes place predominantly at the Wright Research Site in Dayton, Ohio. AFRL, along with NASA, is undertaking advanced development activity on Li-ion batteries for satellites.

The total US Air Force expenditure on RD&D into EES is approximately $0.5 million/year (~£0.3 million/year).

12.2.4 Joint armed forces activity

DARPA
www.darpa.mil

The Defense Advanced Research Projects Agency (DARPA) is the central R&D organisation of DoD. Established in 1960, DARPA has the mission to maintain the technological superiority of the US military and prevent technological surprises from harming national security. It does this by sponsoring revolutionary research that bridges the gap between fundamental discoveries and their military use.

DARPA's staff, drawn from research teams across the armed forces, manages and directs selected basic and applied R&D projects for DoD and pursues research and technologies where risk and payoff are both very high, and where success may provide dramatic advances for military roles and missions. DARPA has no laboratories or research facilities of its own and hence has very low overheads. Rather, the work is contracted-out to other organisations and companies, with DARPA managing the programmes. DARPA staff view themselves as the venture capital part of defence research.

DARPA is organised into eight groups:

- Defense Sciences
- Microsystems Technology
- Information Processing Technology
- Tactical Technology
- Advanced Technology
- Information Exploitation
- Special Projects
- Joint Unmanned Combat Air Systems

While EES has relevance to most of these groups, the Defense Sciences Office (DSO) – which addresses materials, biology and mathematics – takes the lead in this area.

A typical DARPA project in this area is the Palm Power Program, which has a goal to develop a 20 W power source, in a hand-held package, having 15 times the energy content of the best battery (see Section 11.2.5).

DARPA also actively supports a number of special assistance programmes that have been established to ensure equality in federal procurements. These include the Small Business Innovation Research (SBIR) Program and the Small Business Technology Transfer (SBTT) Program.

DARPA's expenditure on R&D into EES in the Palm Power Program is of the order of $1 million (~£530,000).

12.3 Other federal agency activity

In addition to DOE and DoD, a number of other federal departments and agencies have an interest in EES and are undertaking some degree of RD&D activities. These include:

- National Aeronautics and Space Administration (NASA) – John H Glenn Research Center and Jet Propulsion Laboratory are engaged in RD&D activity on advanced Li-ion-polymer batteries through the Polymer Energy Rechargeable Systems (PERS) Program. This work addresses applications including reusable launch vehicles, planetary orbiters, landers and rovers. Work is also under way with AFRL on power sources (mainly Li-ion batteries) for satellites
- US Department of Transportation (DOT) – safety aspects of vehicle batteries
- Environmental Protection Agency (EPA) – battery disposal, bio-assaying for landfilling

As none of these were visited as part of the mission, no information is available.

12.4 Interagency cooperative activity

Interaction between all the key federal departments and agencies concerned with power sources (including electrochemical technologies) is achieved via the Interagency Advanced Power Group (IAPG). This group brings together the US Army, Navy and Air Force, DOE, NASA, DOT and EPA.

The purpose of the IAPG is to facilitate the exchange of information in the area of advanced power at the technical level of R&D programmes, so as to increase the effectiveness of research efforts by avoiding duplications, identifying gaps and sharing information.

Directed by a Steering Group, the IAPG has five Working Groups:

- Mechanical Working Group (with three Panels covering: terrestrial power; thermal management; aerospace power)
- Chemical Working Group
- Electrical/Systems Working Group
- Nuclear/Magnetohydrodynamics (MHD) Working Group
- Renewable Energy Conversion Working Group

The Chemical Working Group focuses on the areas of EES and conversion, including primary and secondary batteries, primary and regenerative fuel cells, electrochemical capacitors, hybrid systems and advanced concepts. Interests among the Working Group members span basic electrochemistry and material science, component development, modelling and systems development and implementation.

The establishment of the IAPG has led to a significant number of accomplishments, including the following with relevance to EES:

- Creation of interagency programme collaborations, eg:

  - NASA and DoD: advanced Li-based/polymer battery technology development
  - Army and DOE/SNL: Li-SO_2 battery shelf-life issues
  - AFRL and NASA: joint flight experiments demonstrating battery systems

- Cross-agency use of laboratory and analytical facilities

- Programmatic inputs to various focused missions or technology assessments:

  - NASA energy storage technology review
  - DoD/Tri-services power sources analysis activities

- Use of interagency expertise on technology review teams/panels

12.5 State support

A number of individual States have an interest in EES, most notably California and New York State. Both States have established joint funding programmes with DOE to develop and demonstrate ES devices (including electrochemical technologies) at a range of scales and in a range of applications.

In California, this joint funding programme is administered by the California Energy Commission (CEC), while in New York State, the New York State Energy Research and Development Authority (NYSERDA) undertakes that role.

Other States (eg Connecticut, Michigan, etc) are also undertaking some activities in EES, but they were not visited during the mission.

12.5.1 California – CEC-DOE Collaboration on Energy Storage

CEC is the State of California's primary energy policy and planning agency (see www.energy.ca.gov/commission). Created by the Legislature in 1974 and located in Sacramento, the Commission has five major responsibilities:

- Forecasting future energy needs and keeping historical energy data
- Licensing thermal power plants of 50 MW or larger
- Promoting energy efficiency through appliance and building standards
- Developing energy technologies and supporting RE
- Planning for and directing State response to energy emergency

As a result, CEC has a particular interest in increasing the State's electricity storage capacity which, until recently has been entirely pumped hydro ES. In 2001, CEC established a collaborative programme with DOE with the goal of demonstrating cost-effective and broadly applicable ES systems. CEC has contract management responsibilities, with DOE (through SNL) having technical project management responsibilities.

The collaboration has an initial budget of \$8 million (~£4.2 million) over 3-4 years (\$4.1 million from the CEC, \$1.2 million from DOE through OETD's ESS Program, and the balance expected as cost-sharing from industry). To date, three projects have been selected for funding:

- Pacific Gas & Electric (PG&E), CA/ZBB Energy Corporation, Menomonee, Wisconsin (contracted) – 2 MW, 2 MWh zinc-bromine flow battery to operate in stand-alone mode to supply extra power to relieve congestion at a PG&E substation. The installation will be mobile so that it can be deployed wherever the most serious peaking load occurs. Testing is expected to commence in mid-2005

- Palmdale Water District, Palmdale, California/Maxwell Technologies, San Diego, California (under negotiation) – 450 kW ultracapacitor to stabilise a microgrid with a 950 kW wind turbine installed at a water treatment plant. During power outages, the ultracapacitor will provide 'ride through' for critical loads until emergency generation can be brought on-line. By providing reliable energy for the microgrid, the project will in turn help reduce T&D congestion in the area
- Independent System Operator, San Ramon, California/Beacon Power Corporation, Wilmington, Massachusetts (under negotiation) – eight 250 kW flywheel ES devices to be combined to provide grid support and frequency regulation. The system specification is 120 kW in charge mode and 100 kW/15 minutes in discharge mode. This project replaced a cancelled project with Urenco Power Technologies (UK) 400 kW flywheel system for the San Francisco Municipal Railway (Muni) system

Two other projects are currently under consideration. The first involves re-applying expended EV batteries for a load-levelling application. The second seeks to deploy a micro-CAES system with above-ground air storage in a peak-shaving application together with heating/cooling load.

12.5.2 New York State – Joint DOE-NYSERDA Storage Initiative

NYSERDA (www.nyserda.org) is a public benefit corporation established in 1975. It conducts R&D activities in five broad areas:

- Enhancing competitive energy markets
- Ensuring energy supply and reliability
- Protecting environmental quality
- Promoting sustainable business development
- Serving the State's residential, small business and low-income customers' needs

In 1995, its mission was broadened to include engineering functions, energy analysis and energy planning, and in 1998 it assumed responsibility for the New York 'Energy $mart Programs' (ie delivery of energy efficiency services).

NYSERDA's total budget was ~$157 million (~£83 million) for FY2002/03, of which the lion's share was from regulatory instruments, eg derived from the System Benefits Charge (non-bypassable charge on electricity utility T&D systems) and the NY Energy $mart Programs – these funds can only be used to benefit grid electricity users, eg subsidies for energy efficiency measures or as 'buy-down' grants for approved products. This has been used to support the purchase of hybrid electric buses, fuel cells and microturbines, and attempts to address some of the market disincentives. Approximately $50 million/year (~£26 million/year) of the overall budget is for R&D activities (some $18 million – £9.5 million – from statutory instruments).

In 2004, NYSERDA and DOE established a joint ES initiative similar to the existing collaboration on ES with CEC (see 12.5.1 above).

The Joint Storage Initiative has a budget of $7.1 million (~£3.7 million) over a three-year period ($2.6 million provided by NYSERDA, $0.9 million by DOE through OETD's ESS Program, and the balance expected as cost-sharing by awardees).

In October 2004, two major ES projects were awarded funds under the initiative to demonstrate advanced electricity ES:

- New York Power Authority, White Plains, New York/NGK Insulators Ltd (under negotiation) – using an Na-S battery system to shift a compressor peak load to off-peak capacity and provide emergency backup power at a major Long Island Bus depot facility. The primary application will be to supply up to 1 MW of power to a gas-fired compressor for 6-8 hours/day, seven days a week. ABB Inc will provide the turnkey system, which will incorporate NGK's Na-S battery

- Niagara Mohawk, Amsterdam, New York/ Beacon Power Corporation, Wilmington, Massachusetts (under negotiation) – using a high-energy flywheel ES system to provide grid frequency regulation and hence grid stability on NM's distribution grid. The demonstration will consist of a 50-100 kW system of seven Beacon flywheels. Additional benefits will include local voltage stabilisation and reactive power, reduction of operational costs, and improved power quality

In addition, five smaller analysis, development and demonstration projects for novel ES have also been selected:

- Gaia Power Technologies, New York, NY (under negotiation) – demonstration of commercial sealed-VLRA battery ES device in 'edge-of-grid' application

- AFS Trinity Power Corporation, Livermore, California (under negotiation) – development of a rotor for advanced flywheel power systems

- Distributed Utility Associates, Livermore, California (under negotiation) – market analysis of ES in New York State

- EPRI PEAC Corporation, Knoxville, Tennessee (under negotiation) – market analysis studies

- Ridge Energy Storage & Grid Services, Houston, Texas (under negotiation) – analysis of the use of mini-CAES for transmission congestion relief

12.6 Summary of federal and State support for EES

Exhibit 12.3 is an attempt to quantify the total federal and State RD&D support for EES.

US FEDERAL AND STATE SUPPORT FOR EES RD&D		
Federal/State agency	Annual support ($ million) approx	Notes
Department of Energy (DOE)		
– OETD: ESS Program	7.5	DOE estimate $7-8 million
– EERE: FCVT Program	23	DOE data
Department of Defense (DoD)		
– TACOM and TARDEC	10	Average of FY2004 and FY2005
– CECOM and CERDEC	23	CERDEC data
– ARO, ARL and ISN	5	Estimate (includes SBIR/SBTT)
– OnPoint Technologies	3.5	Portfolio indicates $3-4 million
– ONR and NAVSEA	30	Estimate, includes NAVSEA, NAVAIR, ONR (includes SBIR/SBTT)
– AFRL	0.5	Estimate
– DARPA	1	Palm Power Program only, FY2004
Other Federal agencies		
– NASA	0.5	Estimate
– DOT	Very small	
– EPA	Very small	
Total Federal support	104	
States		
– California	0.5	DOE estimate
– New York State	0.5	DOE estimate
– Others	Very small	
Total State support	1	
Total – Federal and State	105	

Exhibit 12.3 US Federal and State support for EES RD&D

13 OTHER ACTIVITY

13.1 Academic institutions

A large number of US universities and other academic institutions are actively involved in researching EES technologies. The list in Exhibit 13.1 comprises those institutions that are actively involved in various federal programmes (DOE and DoD), together with those institutions that are collaborating with the private sector organisations visited during the course of the mission. As such, it should not be considered to be exhaustive.

Arizona State University
Cape Western Reserve University
Clark Atlanta University
Clemson University
Georgia Institute of Technology
Illinois Institute of Technology
Massachusetts Institute of Technology
Michigan State University
Michigan Technological University
New Mexico State University
North Carolina State University
Ohio State University
Ohio University
Pennsylvania State University
Prairie View A&M University
Rensselaer Polytechnic Institute
Rice University
Rutgers University
State University of NY at Binghamton
State University of NY at Stony Brook
Texas A&M University
Tufts University
University at Albany
University of Alaska
University of Bridgeport
University of California, Berkeley
University of California, Los Angeles
University of California, Santa Barbara
University of Connecticut
University of Idaho
University of Illinois at Urbana-Champaign
University of Maryland
University of Michigan
University of Minnesota
University of Missouri-Rolla
University of New Mexico
University of Notre Dame
University of Pennsylvania
University of Pittsburgh
University of Puerto Rico
University of South Carolina
University of Texas at Austin
University of Utah
University of Wisconsin-Madison
Virginia Polytechnic Institute
Yale

Exhibit 13.1 US universities and other academic institutions researching EES (not comprehensive)

13.2 Industry associations, alliances and consortia

13.2.1 Electricity Storage Association (ESA)

www.electricitystorage.org

ESA is a trade association established with a mission to promote the development and commercialisation of competitive and reliable ES delivery systems for use by electricity suppliers and their customers. ESA now has a membership of over 50 electricity utilities, storage device manufacturers and developers (advanced batteries, flywheels, SMES, and component suppliers, such as power conversion systems), researchers and R&D funding organisations from the USA, Canada, UK, Switzerland, the Netherlands, Australia and Japan. The UK members are Urenco Ltd and Swanbarton Consultants Ltd.

ESA's goals are to:

- Promote the commercial application of ES technologies as solutions to power and energy problems
- Coordinate and attract international interest and involvement in ES
- Provide a forum for technical and commercial information exchange between suppliers, customers, and researchers

The association grew out of a need to provide an information exchange forum for battery ES following completion of EPRI's Chino Battery Storage Project review group in 1991. The resulting Utility Battery Group was established by more than 30 utilities. In 1996 it broadened its charter and became a trade association to encompass all ES technologies, in recognition of the interest to provide technological solutions to its constituents rather than championing a single technology. In 2001, the organisation was renamed the Electricity Storage Association.

ESA's website contains a lot of useful information on ES technologies and some very informative technology comparisons, some of which have been presented in Chapter 1 of this report.

13.2.2 Electric Power Research Institute (EPRI)

www.epri.com

EPRI was established in 1973 as an independent, non-profit centre for electricity and environmental research. EPRI's collaborative S&T portfolio now spans every aspect of power generation, delivery and end-use, drawing upon a world-class network of scientific, engineering and technical talent. EPRI's clients represent over 90% of the electricity generated in the USA. International client participation represents over 10% of EPRI's programme investment. This includes E.ON UK plc in the UK.

Through collaboration, EPRI is able to leverage the collective resources of its clients to address key industry challenges related to generation, delivery and end-use, with a special focus on safe, reliable, cost-effective electricity and environmental stewardship.

EPRI has more than 900 patents to its credit, and a world-class staff whose expertise spans technology fields and the globe.

EPRI's Energy Storage R&D Program, which has been funded for around 30 years, now aims to provide credible, timely data on the cost, benefit, performance and technology readiness of ES options to enable decision makers to make cost-effective business decisions for deploying ES options.

The key drivers behind this programme are:

- EPRI Electricity Technology Roadmap (www.epri.com/roadmap) – started in 1997 and has identified ES as one of 14 'difficult challenges (DCs)', with it also being an

enabling technology in four other DCs (transmission capacity, increased power quality, grid security and digital society infrastructure)
- CEIDS (see Section 13.2.3)
- DOE 'Grid 2030' National Vision (www.electricity.doe.gov) – a consultative activity led by OETD and started in 2003; low-cost ES has been identified as a key enabling technology

R&D activities under this programme have included:

- Preparing the EPRI/DOE 'Handbook of Energy Storage for Transmission and Distribution Applications', published in December 2003 and currently being revised
- Field trials of promising prototype and emerging ES options
- Examining ES to mitigate stability-limited transmission systems
- Developing the technology of ES options for improved transmission and distribution asset utilisation

13.2.3 Consortium for Electric Infrastructure to Support a Digital Society (CEIDS)

www.ceids.com

CEIDS is an initiative of EPRI and the Electricity Innovation Society. Started in 2001, CEIDS aims to provide the S&T to ensure an adequate supply of high-quality, reliable electricity to a digital economy and integrate energy users and markets. The demands of the emerging 'digital society' infrastructure are for constantly available, digital-grade (ie '9-nines' – 99.9999999%) assets and services, including electricity.

To address these demands, CEIDS has established three critical goals:

- Lead in anticipating and meeting tomorrow's electric energy needs

  - Apply combinations of the most advanced technologies
  - Manage the critical link between economic productivity and power quality
  - Identify the new weak links, pressure points, and critical components impacted by the new uses of the US electricity delivery system that expose them to failure or attack

- Enhance value for CEIDS partners

  - For electric industry partners: maximise asset utilisation and leverage the digital infrastructure in ways that both control costs and boost customer satisfaction
  - For government policy makers and their constituents: continue the acceleration of productivity growth; enable customer choice by introducing efficient technologies and facilitating truly open markets; and cut overall energy needs and costs
  - For digital equipment producers and users: ensure the availability of highly reliable, high-quality power; reduce the energy needs and costs of powering digital systems and related physical plants; and facilitate a wide range of providers

- Create and foster opportunities to enable a digital-quality power supply

  - Leverage the advantages of distributed resources
  - Define and facilitate value-added electricity services
  - Provide new DC electricity supply technologies
  - Develop and deploy advanced power conditioning, power-quality devices and power electronics
  - Establish new service quality standards for electricity and related products

13.2.4 US Advanced Battery Consortium (USABC)

www.uscar.org

USABC is a consortium formed under the US Council for Automotive Research (USCAR) – see Section 12.1.2.

USABC was formed in 1991 with a mission to pursue R&D of advanced energy systems capable of providing future generations of EVs with significantly increased range and performance.

To address this, USABC has set a number of goals:

- Establish the technical capability for advanced battery manufacturing in the USA for EVs
- Accelerate the market potential of EVs by supporting R&D of the most promising advanced battery alternatives
- Develop electrical energy systems capable of providing EVs with range and performance competitive to gasoline-powered vehicles
- Leverage funding for high-risk, high-cost, advanced battery R&D for EVs

USABC is very actively involved in the DOE/USCAR FreedomCAR Partnership and has a coordinating role in the ES RD&D effort within the FCVT Program (see Section 12.1.2). These efforts are addressing innovative batteries for a wide range of vehicle applications, including HEVs, EVs, potential 42 V vehicular systems, and FCVs/HFCVs.

13.2.5 Advanced Lead-Acid Battery Consortium (ALABC)

www.alabc.org

ALABC is a research consortium originally formed in 1992 to advance the capabilities of the valve-regulated LA battery in order to help EVs become a reality. The research resources of the worldwide membership (currently 45 organisations) are pooled in order to carry out a large programme of R&D.

In a new phase of R&D – January 2003 to December 2005 – ALABC is focusing on the end markets of 42 V and HEV systems. The goal remains to achieve performance enhancements which will allow the VRLA battery to succeed in all the important markets that are now in prospect. These include the telecommunications, remote area power supply, 36/42 V automotive systems and HEV markets.

ALABC is managed by the International Lead Zinc Research Organisation Inc (ILZRO), based in Research Triangle Park, North Carolina.

R&D activities include:

- Batteries for HEVs

  - Foresight vehicle project: Reliable Highly Optimised Lead-Acid Battery (RHOLAB)

- Negative plates

  - Optimisation of the negative active material and partial state-of-charge (PSoC) cycle-life of VRLA batteries for 42 V mild hybrid applications
  - Optimisation of additives to the negative active material for the purpose of extending the life of VRLA batteries in high-rate PSoC (HRPSoC) operation
  - Development of additives in negative active material to suppress sulphation during HRPSoC operation
  - Estimation of the influence of trace elements on the performance of VRLA batteries at high temperatures and under HRPSoC operation

- Separators/compression
  - Evaluation of different glass microfibre separators and membranes for VRLA batteries working on HRPSoC
  - Development of separator systems for VRLA batteries in HRPSoC duty
- System integration
  - ISOLAB42 – a continuation of the RHOLAB project (includes a number of UK partners)

14 MAJOR OUTCOMES

The following sections cover the major outcomes of the mission – the key messages learned, the opportunities identified for the UK and, finally, the recommendations from the mission.

The coverage of this mission was considerable but crucial to everyday life as well as industry, business and military needs. As a result, the team identified a considerable number of 'learning points' for UK companies, universities and other research organisations, as well as government. Many of these have been presented in the preceding chapters of this report. Section 14.1 below attempts to pull out what the team considered to be the key messages from the mission.

The ramifications of a 'wait and see' policy in the UK could be costly, the more so as scientific and technological endeavour, coupled with innovative engineering solutions, are being pursued on many fronts in order to meet a multitude of complex renewable energy problems as well as enhancing electrochemical energy storage. As with all areas of development, benefit and cost – together with risk – need to be carefully weighed and understood.

What is apparent is that a great deal of preparatory work has been done by researchers and industrialists in this field in the USA, such that market growth could be very rapid once a 'tipping point' is reached. Undoubtedly there are opportunities for UK companies and research organisations in the UK, and some of the more immediate opportunities identified during the mission are presented in Section 14.2.

As a result of this intensive and very informative Global Watch Mission, the mission team has a number of recommendations for UK industry, academia and government. These are presented in Section 14.3.

14.1 Key messages

Energy storage (ES) systems (including, but not limited to, electrochemical systems) are becoming of increasing interest as an important enabling technology in stationary, transport and portable applications, both civil and military. Some transfer of technology between these markets is evident, particularly from the automotive transport sector.

A number of **electrochemical energy storage (EES) technologies** are currently being deployed in a variety of civil and military applications.

Despite being a well established technology, **lead-acid (LA) batteries** remain very competitive in terms of performance and cost, with improvements continuing to be made. Furthermore, improvements of the order of 30% in energy densities are anticipated. They are still one of the most cost-effective forms of EES as well as being extremely reliable.

LA batteries are heavily used for most applications requiring power storage: integrating renewable energy sources, microgrid systems, UPS systems, etc. Nothing seen during the course of this mission led the team to believe that any change in this approach was imminent.

A wide range of **advanced battery chemistries** are being researched, developed and demonstrated in the USA. These technologies are aiming for improvements in energy density, power density or both, at acceptable cost. In general, these technologies are some way from being commercial and should be viewed as mid-to-long term in terms of market impact: there could be a doubling and even quadrupling of rechargeable battery energies over the next 10 to 20 years. All such chemistries are based on one valence jump, although fundamental research is also under way to try and achieve a double valence jump.

Lithium-ion (Li-ion) and **nickel-metal hydride (Ni-MH) batteries** may be close to maturity, and are now finding many applications where their higher initial costs are acceptable. These include many transport and military applications.

Saft's high-power, Li-ion technology appears to be the battery system of choice for electric vehicles (EVs) and hybrid electric vehicles (HEVs) in military, commercial and civil applications.

While research into improved performance, lower cost and safer cathode materials for Li-ion rechargeable batteries is being undertaken in the USA (comparable to that under way in the UK), no innovative research into insertion cathode or anode materials was evident during the course of the mission.

MIT has developed a number of **lithium-metal-polymer (LMP)** 'pouch' cells based on lithium anodes with a dry solid polymer electrolyte based on block copolymers. These cells can be made with a flexible form factor and achieve specific energies up to 400 Wh/kg. They have negligible vapour pressure, and since no liquid or gel electrolyte is used, may be suitable for medical implant use.

The Army Research Laboratory (ARL) is investigating **lithium-iron phosphate** as an alternative low-cost and safer cathode material for rechargeable systems. However, the synthesis of this material in a conducting form is a major challenge. It is also looking at low-temperature carbon monofluoride (CFx) as a cathode for **primary lithium-CFx batteries**. The low-temperature material has a much better electronic conductivity and is much better suited to higher rate performance.

Future advanced batteries with significantly higher energy densities look likely to be based on lithium chemistry – both **lithium-sulphur** and **lithium-air**: Sion Power has demonstrated an Li-S rechargeable battery with an energy density of 350 Wh/kg and this is anticipated to rise to 400 Wh/kg soon, with 600 Wh/kg expected in the future. Meanwhile, PolyPlus Battery Co has demonstrated a novel lithium coating, which paves the way for a 1,000 Wh/kg Li-air battery in the future.

Ultracapacitors are an emerging technology which appears to be on the point of becoming cheap enough for use in a very wide variety of applications. Ultracapacitors probably represent one of the most exciting developments in short-term ES seen during the mission.

At MIT, the possible use of carbon nanotubes in ultracapacitors is being investigated with the aim of bringing their performance close to that of a battery, although numerous practical issues remain to be addressed before realising the potential energy density.

The use of **flow cell ('redox') batteries** to store energy in liquid electrolytes is being demonstrated in the USA. Two US manufacturers (VRB – based on a **vanadium-vanadium couple** – and ZBB – based on a **zinc-bromine couple**) have established a clear lead in the commercialisation of such technology, with multi-megawatt units now in service.

A third US-based technology, developed by Plurion Systems and based on a **zinc-cerium couple**, is available which has the advantage of not requiring the high-cost ion exchange membranes that limit the cost effectiveness and life of the other technologies.

The US military could become a significant 'early adopter' for advanced battery and ultracapacitor technologies – 10% of new US combat vehicles are expected to be HEVs with exportable AC power.

Various problems can arise when integrating **intermittent renewable energy (RE) sources** (eg wind energy and solar photovoltaic (PV) energy). If this input exceeds a level that can be as low as 5-15% of the total capacity of the local electricity infrastructure, then instability can occur as the source fluctuates. To limit such instability, groups such as EPRI are examining the potential role of ES including battery energy storage systems (BESS): such systems allow for immediate control by absorbing excess energy and releasing it when needed.

Local, more **distributed generation** from RE sources is seen as a key way to improve sustainable energy availability. However, the design must incorporate improved management of all system components in a controlled infrastructure. A possible way to achieve this is to build an integrated **'microgrid'** that is capable of stand-alone operation as well, where appropriate, interconnection and synchronisation with major transmission and distribution infrastructure.

The use of ES is widely recognised as an important means of **reducing 'spinning reserve'** capacity requirements cost effectively. This concept would help RE power generation respond immediately to a power surge from the ES device, and the carbon-fuelled spinning reserve could then be reduced.

Increasingly, it is the ES **system** that the users/markets are seeking, rather than the storage technology at the cell level *per se*. As such, there is an increasing need for **systems integration** in the USA. The role of the network integrator and the agreement of standards in data transfer and control is becoming crucial to the building and management of distributed energy infrastructure.

With one exception, the organisations visited see a clear role for **fuel cell or fuel cell hybrid systems** in stationary, portable and, particularly, transport applications, especially when considerable energy density is needed over prolonged operation periods. Solid oxide fuel cells (SOFCs), direct methanol fuel cells (DMFCs) and proton exchange membrane fuel cells (PEMFCs) were cited as the leading fuel cell technologies respectively for the above market applications.

There is scope for improving the performance of both batteries and fuel cells by using **advanced/novel-processing methods**.

Federal and state agency funding for the research, development and demonstration (RD&D) of EES technologies and systems is considerable when compared to the UK – of the order of $105 million (~£55 million) per year. However, this compares unfavourably with the high levels of funding available for fuel cell and hydrogen infrastructure RD&D – of the order of $300-500 million (£160-260 million) per year: this disparity has caused a major shift of priorities in both US industry and academia. There is a commonly held view in many of the agencies visited during the mission that not enough practical research has been completed on the role of ES technologies, and that this is a crucial component in a future, more distributed energy network relying on RE sources.

Partly as a result of the above shift in priorities relating to funding, but also, more generally, a **de-skilling in electrochemical storage competencies** has occurred in the USA in the last few years. This is regarded as a significant problem by the industry, particularly in light of the emerging possibilities for EES devices and systems. Japan, China and Korea were cited as examples of countries that are 'tooling-up' to address these market opportunities and the attendant technology challenges.

A multitude of activities concerning EES is under way in research groups and agencies serving the US armed forces. The **coordination of this activity** is complex – with some overlap of activity. At the higher level, coordination is in place and linkage with other federal agencies occurs.

Several strong **industry-government-academia partnerships** are in place in the USA. These initiatives involve a good level of industry cost-sharing, and activities in national laboratories and key US universities.

There is a need (and opportunities) to establish stronger **USA-UK linkages** in collaborative RD&D activities.

14.2 Opportunities identified for the UK

At present, there is no perfect solution to the provision of power to the dismounted soldier in a package of acceptable weight and volume with suitable ruggedness and range of operating conditions. This problem needs a ready solution.

There is also a military need for power generation devices which can operate from military, sulphur-heavy, logistic fuel. The initial applications seen for such devices would be auxiliary power units (APUs) for vehicles, but if the technology could be scaled-down, then there would be interest for soldier-portable power.

Whilst the bulk of US research funding goes to US companies, universities and research organisations, opportunities exist for UK technology developers to have their power sources assessed under programmes such as the Foreign Competitive Test and Evaluation Program operated by CERDEC.

Opportunities exist to collaborate with US military organisations such as the Office of Naval Research (ONR) and the Army Research Laboratory (ARL) and, indeed, such collaboration has taken place in the past (eg involving UK universities). ONR and ARL have a European office based in London that could facilitate such collaboration.

Various EES technologies applicable to RE electricity generation are at the demonstration stage in the USA. The UK would be an excellent location for demonstration of such technologies in Europe.

Consideration is being given to the concept of 'contract ES' (ie where an organisation with a storage need contracts to buy energy at a discounted level from storage plant operators, rather than purchasing an ES system). This would require the strong involvement of finance companies, as well as engineering companies, and presents an opportunity for both sectors.

Furthermore, this represents an opportunity for UK engineers and financial companies to develop resources that may be used first in the UK but will allow them to enter a much larger US market if US policy becomes more favourable to ES and the integration of RE sources.

The identified and growing need for network integrators and the agreement of standards in data transfer and control presents opportunities to UK companies with competencies in such roles.

14.3 Recommendations from the mission

The mission team recommends that:

- Engineering companies should develop, or hold, the range of skills to provide systems integration services in the areas of ES and integration of RE sources. There is a wide array of individual components, each with specific strengths and weaknesses, which need to be applied carefully to match end-users' circumstances. This calls for expertise that will rarely be available to potential energy users, even to assess the benefits of ES

- Government should investigate the need for ES to overcome problems created by the increasing use of intermittent RE sources, fund research and provide incentives similar to those available for RE generation

- A follow-up Global Watch Mission to North America should be considered to specifically examine these issues of ES to enable the further integration of RE sources into the UK's electricity supply. Such a mission could also usefully address power quality, microgrids/distributed generation and interconnection issues

- A close watch should be kept on power source developments in the US military, and collaborations sought where possible. The US armed forces could become a significant 'early adopter' of advanced battery and ultracapacitor technologies – future US combat vehicles and 10% of new US tactical vehicles are expected to be HEVs with exportable AC power

- There is a need for far greater transfer of technology from system development between different applications – most notably between the military and commercial sectors

- Technology and system developers in the UK should consider having their power sources assessed under various US programmes (eg the Foreign Competitive Test and Evaluation Program operated by CERDEC)

- Clear routes for collaboration and funding between the relevant US and UK organisations need to be identified and promoted

- UK universities should consider much closer links with US universities where they have a common electrochemical research objective

- There is a strong need for economic/regulatory incentives to encourage the take-up of ES in mainstream activities

- Government, financiers and those associated with funding issues need to be made aware of developments in the EES field in order to take an innovative approach to the financing of state-of-the-art projects

- Far more concentration of effort should be placed on education of the public in general as to the need to reduce consumption which might even mean legislation in order to reduce demand

- In those cases where UK universities have an electrochemical department, they should be encouraged by government to increase their R&D and, as appropriate, spin-off commercially-viable new businesses

- Government should give serious consideration to supporting the creation of a high-level, dedicated organisation to oversee this area of technology, with the additional remit to review all advances as an ongoing policy, and facilitate collaborative ventures (both inward and outward). This organisation could perhaps mirror the role of Fuel Cells UK

- A short piece of research should be undertaken involving both UK financiers and industry specialists in the area of EES and RE to review the funding criteria adopted in the USA where innovative projects arise

- A mainstream battery magazine should be encouraged to incorporate a section on financing ES projects in order that readers, be they scientists or R&D engineers, might become more familiar with the criteria that financiers would adopt should a business wish to put together a business case for finance

Appendix A

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Appendix B

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Appendix C

MISSION QUESTIONS

Electrochemical energy storage

To review new and emerging electrochemical energy storage devices that are appropriate to: stationary applications including the storage of intermittent renewable energy; portable applications including military uses; telecoms; and transport applications including hybrid electric vehicles. Technologies of interest would include super/ultracapacitors, lead-acid batteries, advanced batteries, metal-air cells and other appropriate storage devices below 10 kW for man-portable systems as well as load-levelling systems.

Technical and electrochemistry

1 What are the practical limits for energy storage in ultracapacitors? Current state -of-the-art?
2 Is it possible to give a numerical estimate of the likely practical limit (eg in J/Kg?) Wh/kg for specific energy, Wh/dm^3 for energy density are preferred units for comparison with other technologies.
3 Are there key factors that adversely affect (reduce) lifetime, such as charge/ discharge cycling, or mechanical factors such as vibration or temperature, etc?
4 What are the limiting temperatures (upper and lower) for ultracapacitor operation using current technology?
5 Optimum renewable energy sources for ratings between 1 kVA and 1 MVA, including comparisons between wind, photovoltaic, wave.
6 Optimum alternative energy sources for ratings between 1 kVA and 1 MVA, such as fuel cells, continuous-flow fuel cells, flow cells.
7 Comparisons of energy density of the various systems.
8 Which systems are appropriate (a) for AC supply and (b) for 48 V DC supply, and the interface methods necessary.
9 Suitability of the various systems for loads situated in urban locations.
10 Safety implications/precautions where different from conventional power systems.
11 Views on Li-metal versus Li-ion electrodes.
12 Design limitations on Li battery size/capacity.
13 Target energy density and current status.
14 Fuel cell/battery comparison.
15 Role of energy storage in national or local grid stability.
16 Energy storage integration in building structures-embedded systems?
17 What alternative engine technologies for hybrid generators.
18 Biofuel application examples.
19 Battery test regimes – partial state of charge.
20 High-rate recharge requirements.
21 Materials developments.
22 Requirements for battery performance.
23 Possibilities for more effective mobile generator technology.
24 Possibilities for novel electricity generation methods.
25 Energy and power density of products.
26 Safety of batteries – certified for air transport?
27 For what applications are you looking at batteries?
28 Which batteries are you considering for these applications and why?

29 What is the greatest constraint on the batteries, eg weight, power, low-temperature performance, etc?
30 Are you considering primary or only secondary batteries?
31 What do you feel will be the upper limit of battery technologies in the next 5-10 years?
32 What are the requirements for the power sources for Land Warrior and associated programmes. Is it envisaged that these power requirements can be met by a single battery system or will a hybrid with another power source be required?
33 Current state-of-the-art Li-ion battery cathodes.
34 State of development of polymer systems.
35 Current state-of-the-art Ni-MH and lead-acid technologies.
36 What are the battery technology drivers and timescales to market?

Economics and environmental

1 (Ultracapacitors) If there is no physical limit on capacity, is there an economic limit (eg a rapidly rising cost of manufacture as size is increased)?
2 What is the likely lifetime of a typical ultracapacitor?
3 Optimum storage methods for AC and low-voltage DC (48 V nominal) systems with ratings between 1 kWh and 5 MWh.
4 Comparisons between conventional batteries, alternative battery couples, fuel cells, flywheels, etc.
5 Environmental impacts, including experience in rural and urban locations, where relevant.
6 Relative economies of the various systems and comparisons with conventional systems.
7 Predictions for trends in relative economies.
8 Ultracapacitor/battery hybrids for HEV and EV applications.
9 Opportunities for licensing technologies and products.
10 Cost/performance comparisons of alternative cathode materials.
11 Comparison of relative merits of Li rechargeable to Ni-MH in different applications.
12 Views on role of energy storage in facilitation of renewable energy introduction.
13 Comparative merits of fuel cell and hybrid vehicles.
14 Comparison of main battery performances and limiting factors to introduction.
15 Commercial status in USA of electric drive vehicles.
16 Ratio of electricity generation by different fuel type in USA.
17 Current battery performance against original targets.
18 Hybrid/fuel cell/battery car performance status.
19 Latest performance and battery sizes.
20 Commercial application status.
21 Views on hybrid versus all-electric vehicles
22 Cost-performance comparison for main battery types studied.
23 What are costs or predicted costs per Wh and per W for your system?
24 Disposal and transportation.
25 How do you qualify your technology for an application?
26 How are renewable energy and energy harvesting technologies such as thermoelectrics and photovoltaics seen to play a role in various applications in the future?
27 What are the preferred technologies for the various driver options?
28 Impact of environmental and global issues on the choice of technology options for various applications.
29 Are lithium-ion batteries to be seen in commercial HEV and EV applications?
30 If so, are safety issues and cost being addressed accordingly?

31 What federal government funding is available to support RD&D activity in electrochemical energy storage?
32 How do such programs operate and how is collaboration encouraged?
33 What are current and future levels of funding?
34 What State programs exist to fund activity in this area?
35 Which universities are prominent in this area?

Marketing

1 Are there any key barriers to high-volume manufacture and use of ultracapacitors for ‘domestic’ or mass-market products such as automobiles?
2 How do ultracapacitors differentiate themselves from competitor energy storage technologies?
3 Incentives for use of ‘green’ methods.
4 Experience with objections from local community.
5 Opportunities for joint venture.
6 Review of strengths and weaknesses of redox energy storage compared to batteries.
7 Conclusions on viability of large-scale battery storage systems from field experience – eg Puerto Rico, California.
8 What are the major barriers to marketing of the technologies?
9 Who are the key players?

Appendix D

COMPARISON OF RECHARGEABLE BATTERY TECHNOLOGIES

Battery type	Specific power W/kg	Energy density Wh/dm^3	Specific energy Wh/kg	Cycle-life (to 80% depth of discharge)	Internal temperature °C	Main battery manufacturers	Stage of development	Common applications
Gelled lead-acid (flat-plate/SLA-VRLA)	100	80	30-40	200	Ambient	Yuasa, Hawker	Commercial	Stationary, traction, UPS, telecom, automotive
Spiral-wound lead-acid (high power-cyclon)	200	60	25-30	200-300	Ambient	Hawker	Commercial	Beacons, transponders, telemetry, signalling, lawnmowers
Bipolar lead-acid (large)	400-600	60	20-25		Ambient	Effpower	Advanced prototype	Stationary, HEV, EV, telecom
Nickel-cadmium (Ni-Cd)	400-1,000	110	20-50	1,000	Ambient	Saft, Panasonic, Yuasa	Commercial	Portable, stationary, military, motive
Nickel-metal hydride (Ni-MH)	260-1,100	200-300	30-100	500	Ambient	Saft, Varta, Cobasys, Panasonic	Commercial (small cells, 6.5 Ah cells and modules for HEV and EV), advanced prototype (Cobasys HEV battery modules)	Portable, HEV, traction, military
Lithium-ion high energy (Ni/Co-based cathode)	340-400	308	130-170	500-1,000	Ambient	Saft, Varta, AEA Technology	Commercial, small cells Advanced prototype, large cell modules for HEV	Portable, military, HEV, EV, traction
Lithium-ion high power (Ni-based cathode)	1,300-1,600	160	70	1,000	Ambient	Saft, AEA Technology	Advanced, prototype HEV and EV modules	HEV, military

Battery type	Specific power W/kg	Energy density Wh/dm^3	Specific energy Wh/kg	Cycle-life (to 80% depth of discharge)	Internal temperature °C	Main battery manufacturers	Stage of development	Common applications
'Saphion' (lithium-iron phosphate)		340	170	1,000	Ambient	Valence Technology	Advanced prototype	Portable, military, stationary
Saphion-polymer (gel electrolyte)		260	130	600–1,000	Ambient	Valence	Advanced prototype	Portable
Lithium-ion-polymer (LIP) (gel electrolyte)	200-300	260	130	1,000	Ambient	Ultralife, Varta, Danionics, Valence Technology	Commercial	Portable, military
Lithium-water and lithium-air	1-2 mW/cm^2	1,000	1,000-3,000 (projected based on anode)	Not yet determined	Ambient	PolyPlus	Research prototype	Military, HEV
Lithium-metal-polymer (LMP) (dry polymer)	241	200-300	120-130	300	40-60	Avestor	Advanced prototype	Stationary, telecom
Lithium-metal-polymer (dry polymer)			300	Not yet determined	40-60	MIT-Sadoway	Research prototype	Biomedical
Lithium-sulphur	>1,000?	350 - 400	350-400	50	Ambient	Sion Power	Second generation prototype	Military, portable, HEV
'Zebra™' (sodium-metal chloride)	164-295	600	90-120	2,500-3,000	300	Beta R&D	good	HEV, military, stationary

Appendix E

GLOSSARY OF ABBREVIATIONS

µ	chemical potential
µF	microfarad
µm	micrometre
σ	specific electrical conductance
$	US dollar (£1 ≈ $1.9)
a	anode
A	amp(ere)
AAGR	average annual growth rate
AC/ac	alternating current
ACONF	alternative configuration (battery charging)
AEA	Advanced Energy Analysis (USA)
AEP	American Electric Power (USA)
AFRL	Air Force Research Laboratory (US Air Force)
Ah	amp(ere)-hour
AJCN	Adaptive Joint CISR Node (programme, DoD)
AK	Alaska (USA)
Al	aluminium
ALABC	Advanced Lead-Acid Battery Consortium (USA)
ANL	Argonne National Laboratory (DOE)
APU	auxiliary power unit
ARL	Army Research Laboratory (US Army)
ARO	Army Research Office (US Army)
ASDV	advanced swimmer delivery vehicle
ATC	air traffic control
AZ	Arizona (USA)
BCE	block copolymer electrolyte
BESS	battery energy storage system
BLA	bipolar lead-acid
BIOS	basic input/output system
BNL	Brookhaven National Laboratory (DOE)
Br	bromine
BTU	British thermal unit (= 1055 kJ)
c	(1) cathode; (2) US cent
C	coulomb
ºC	degrees Celsius
Ca	calcium
CA	California (USA)
CAES	compressed air energy storage
CAR	Cooperative Automotive Research
Cd	cadmium
Ce	cerium
CEC	California Energy Commission (USA)
CECOM	Communications-Electronics Command (US Army)
CEIDS	Consortium for Electric Infrastructure to Support a Digital Society (USA)
CERDEC	Communications-Electronics Research, Development and Engineering Center (US Army)
CERTS	Consortium for Electric Reliability Technical Solutions (USA)
CES	chemical energy storage
CFx	carbon monofluoride
CHP	combined heat and power
CISR	communications, intelligence, surveillance and reconnaissance
cm	centimetre
Co	cobalt
CO	Colorado (USA)
CR	Centro Ricerche (Fiat)
CTA	Collaborative Technology Alliances (programme, ARL)
CY	calendar year
D	depth
DARPA	Defense Advanced Research Projects Agency (DoD)
DC/dc	(1) District of Columbia (USA); (2) direct current; (3) 'difficult challenge' (EPRI)
DER	distributed energy resources
DETL	Distributed Energy Test Laboratory (SNL)
DLC	double-layer capacitor
dm	decimetre
DMFC	direct methanol fuel cell
DoD	Department of Defense (USA)
DOD	depth of discharge
DOE	Department of Energy (USA)
DOT	Department of Transportation (USA)

DR	demand response
DSO	Defense Sciences Office (DARPA)
DSTL	Defence Science and Technology Laboratory (MOD, UK)
DTI	Department of Trade and Industry (UK)
e	electron
E	energy
E_a	redox energy (anode)
E_c	redox energy (cathode)
E_g	band-gap energy
ECS	Electrochemical Society (USA)
EDA	Electrochemical Design Associates Inc (USA)
EE	electrochemical energy
EERE	Office of Energy Efficiency and Renewable Energy (DOE)
EES	electrochemical energy storage
EJ	exajoule (= 10^{18} joule)
EPA	Environmental Protection Agency (USA)
EPRI	Electric Power Research Institute (USA)
ES	energy storage
ESA	Electricity Storage Association (USA)
ESS	Energy Storage Systems (programme, DOE)
EV	electric vehicle
F	Faraday constant
FCV	fuel cell vehicle
FCVT	FreedomCAR and Vehicle Technologies (programme, DOE)
Fe	iron
FEMA	Federal Emergency Management Agency (USA)
FFW	Future Force Warrior (initiative, US Army)
FL	Florida (USA)
FY	fiscal year
g	gram
GHG	greenhouse gas
GPE	graft copolymer electrolyte
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GTO	gate turn-off (thyristor)
GVEA	Golden Valley Energy Authority (Fairbanks, Alaska, USA)
GW	gigawatt (= 10^9 watt)
h	hour
H	(1) hydrogen; (2) height
H_2O	water
H_2SO_4	sulphuric acid
HEFC	hybrid electric fuel cell (vehicle)
HEV	hybrid electric/ICE vehicle
Hf	hafnium
HFCV	hybrid fuel cell vehicle
HICE	hydrogen ICE
HMMWV	high-mobility multipurpose wheeled vehicle ('Humvee')
HRPSoC	high-rate PSoC
Hz	hertz (= cycle/s)
i	current density
IAPG	Interagency Advanced Power Group (USA)
ICE	internal combustion engine
IEC	International Electrotechnical Commission
IED	improvised explosive device
IEEE	Institute of Electrical and Electronics Engineers (USA)
IGCT	integrated gate commutated thyristor
ILZRO	International Lead Zinc Research Organisation (USA)
INEEL	Idaho National Engineering and Environmental Laboratory (DOE)
IP	(1) intellectual property; (2) Internet Protocol
IPSS	International Power Sources Symposium (UK)
ISN	Institute for Soldier Nanotechnologies (MIT/US Army)
IST	Integrated Soldier Technology (programme, UK)
IT	information technology
ITP	International Technology Promoter (DTI)
J	joule
JET	Joint European Torus (UK)
JP-8	logistic aviation fuel
JV	joint venture
K	kelvin
kg	kilogram
kJ	kilojoule
kPa	kilopascal
kV	kilovolt

kVA	kilovolt-amp(ere)
kVAR	reactive power
kW	kilowatt
kWh	kilowatt-hour
ℓ	litre
LA	lead-acid
LBNL	Lawrence Berkeley National Laboratory (DOE)
LCD	liquid crystal display
Li	lithium
LIB	lithium-ion battery
Li-CFx	lithium-carbon monofluoride
$LiCoO_2$	lithium cobalt oxide
$LiFePO_4$	lithium iron phosphate
Li_2FeS_2	lithium iron disulphide
Li-ion	lithium-ion
$LiMn_2O_4$	lithium manganese oxide
LiN	lithium nitride
$LiNiO_2$	lithium nickel oxide
LiOH	lithium hydroxide
LIP	Li-ion-polymer
LiPON	lithium phosphorus oxynitride
Li-S	lithium-sulphur
LISICON	lithium super-ionic conductor
Li-SO_2	lithium-sulphur dioxide
LMP	lithium-metal-polymer
LSBU	London South Bank University (UK)
m	metre
mA	milliamp(ere)
MA	Massachusetts (USA)
MCFC	molten carbonate fuel cell
MD	Maryland (USA)
MEMS	micro-electro-mechanical systems
Mg	magnesium
MH	metal hydride
MHD	magnetohydrodynamics
MI	Michigan (USA)
min	minute
MIT	Massachusetts Institute of Technology (USA)
mm	millimetre
Mn	manganese
MnO_2	manganese dioxide
MOD	Ministry of Defence (UK)
mol	mole
ms	millisecond
MTBF	mean time between failure
MVA	megavolt-amp(ere)
mW	milliwatt
MW	(1) megawatt; (2) molecular weight
N	nitrogen
Na	sodium
NaBr	sodium bromide
NAC	National Automobile Center (TARDEC)
Na-$NiCl_2$	sodium-nickel chloride ('Zebra')
NaS	sodium sulphide
NASA	National Aeronautics and Space Administration (USA)
NAVAIR	Naval Air Systems Command (US Navy)
NAVSEA	Naval Sea Systems Command (US Navy)
NAVSSES	Naval Ship Systems Engineering Station (US Navy)
NC	North Carolina (USA)
NERC	North American Electric Reliability Council
nF	nanofarad (= 10^{-9} F)
Ni	nickel
Ni-Cd	nickel-cadmium
Ni-MH	nickel-metal hydride
NJ	New Jersey (USA)
NM	(1) New Mexico (USA); (2) Niagara Mohawk (utility, USA)
NREL	National Renewable Energy Laboratory (DOE)
NSWC	Naval Surface Warfare Center (US Navy)
NYSERDA	New York State Energy Research and Development Authority (USA)
O	oxygen
O&M	operation and maintenance
OC	open circuit
OEM	original equipment manufacturer
OETD	Office of Electric Transmission and Distribution (DOE)
OFW	Objective Force Warrior (programme, US Army)
OH	Ohio (USA)
ONR	Office of Naval Research (US Navy)
p	pence
P	phosphorus
Pa	pascal
PA	Pennsylvania (USA)
Pb	lead
PbO_2	lead dioxide

$PbSO_4$	lead sulphate
PC	personal computer
PCS	power conversion system
PDA	personal digital assistant
PEM	proton exchange membrane
PEMFC	polymer electrolyte membrane fuel cell / proton exchange membrane fuel cell
PEO	Program Executive Office (US Army/Navy)
PERS	Polymer Energy Rechargeable Systems (Programme, USA)
pF	picofarad (= 10^{-12} F)
PG&E	Pacific Gas and Electric Co (USA)
PHS	pumped hydro storage
PIER	Public Interest Energy Research (programme, CEC)
PLiON	Li-ion-polymer
POEM	poly (oxyethylene methacrylate)
PR	Puerto Rico
PREPA	Puerto Rico Electric Power Authority (USA)
PSB	polysulphide bromide battery
PSCOE	Power Sources Center of Excellence (CECOM)
psi	pounds per square inch
PSoC	partial state of charge
PTC	positive temperature coefficient (thermistor)
PV	photovoltaic
PWh	petawatt-hour (= 10^{15} watt-hour)
QC	Quebec (Canada)
Quad	quadrillion (10^{15}) BTU
R&D	research and development
RD&D	research, development and demonstration
RDECOM	Research, Development & Engineering Command (US Army)
RE	renewable energy
redox	reduction/oxidation
RF	radio frequency
RHOLAB	Reliable Highly Optimised Lead-Acid Battery (ALABC Foresight vehicle project)
RPG	rocket-propelled grenade
RTG	radioisotopic thermoelectric generator
s	second
S	(1) siemens (= 1/ohm = mho); (2) sulphur
S&T	science and technology
SBIR	Small Business Innovation Research (programme, USA)
SBTT	Small Business Technology Transfer (programme, USA)
SCADA	supervisory control and data acquisition
SEI	solid electrolyte interface
SF	San Francisco (CA)
SHE	standard hydrogen electrode
SI	Système International (d'Unités)
SINCGARS	Single Channel Ground and Airborne Radio System
SLI	starting, lighting and ignition (automotive power)
SMES	superconducting magnetic energy storage
SNL	Sandia National Laboratories (DOE)
SOA	state-of-the-art
SOFC	solid oxide fuel cell
STS	source transfer switch
SUV	sport(s) utility vehicle
T&D	transmission and distribution
TACOM	Tank-automotive and Armaments Command (US Army)
TARDEC	Tank-Automotive Research, Development and Engineering Center (US Army)
TEPCO	Tokyo Electric Power Co (Japan)
Tg	glass transition temperature
Ti	titanium
TiS_2	titanium disulphide
TN	Tennessee (USA)
TNO	Nederlandse Organisatie voor Toegepast-Natuurwetenschappelijk Onderzoek – Netherlands Organisation for Applied Scientific Research
TNT	trinitrotoluene
TV	television
TWh	terawatt-hour (= 10^{12} watt-hour)
TX	Texas (USA)
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
UK	United Kingdom
UL	Underwriters Laboratories Inc (USA)

ultracap	ultracapacitor (known as supercapacitor in the UK)
UN	United Nations
UPS	uninterruptible power supply
US(A)	United States (of America)
USABC	US Advanced Battery Consortium
USAID	US Agency for International Development
USCAR	US Council for Automotive Research
UT	Utah (USA)
UUV	unmanned underwater vehicle
V	(1) volt; (2) voltage; (3) vanadium
V_2O_5	vanadium pentoxide
V_{OC}	open-circuit voltage
VA	Virginia (USA)
VC	venture capital
VLA	vented LA
VRB	vanadium redox battery
VRLA	valve-regulated LA
VW	Volkswagen AG (Germany)
W	(1) watt; (2) width
Wh	watt-hour
WI	Wisconsin (USA)
WIN-T	Warfighter Information Network – Tactical (programme, US Army)
yr	year
Zn	zinc
Zn-Br	zinc-bromine
$ZnBr_2$	zinc bromide

Appendix F

LIST OF EXHIBITS

The DTI's Global Watch Service provides support dedicated to helping UK businesses improve their competitiveness by identifying and accessing innovative technologies and practices from overseas.

Global Watch Information
Global Watch Online – a unique internet-enabled service delivering immediate and innovative support to UK companies in the form of fast-breaking worldwide business and technology information. The website provides unique coverage of DTI, European and international research plus business initiatives, collaborative programmes and funding sources.
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Global Watch Secondments – helping small and medium sized companies to send employees abroad or receive key people from another country. Secondments are an effective way of acquiring the knowledge, skills, technology and connections essential to developing a business strategically.
Contact:
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Global Watch Technology Partnering – providing free, flexible and direct assistance from international technology specialists to raise awareness of, and provide access to, technology and collaborative opportunities overseas. Delivered to UK companies by a network of 18 International Technology Promoters, with some 6,000 current contacts, providing support ranging from information and referrals to more in-depth assistance with licensing arrangements and technology transfer.
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For further information on the Global Watch Service please visit
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