

Policy Department
Economic and Scientific Policy

OUTLOOK OF ENERGY STORAGE TECHNOLOGIES

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TABLE OF CONTENTS

Executive Summary	i
1. Energy Storage.....	1
1.1 Introduction	1
1.2 Scope of this Study.....	3
1.3 Applications of Energy Storage Technologies.....	3
1.3.1 Electricity Network Energy Storage	4
1.3.2 Transport and Mobility Energy Storage Applications.....	5
1.4 Economics of Energy Storage	6
1.4.1 Economics - electricity network energy storage.....	6
1.4.2 Economics – battery electric vehicles.....	7
1.5 Energy Storage and Greenhouse Gas Emissions.....	7
1.5.1 Electricity Network Energy Storage and Greenhouse Gas Emissions.....	7
1.5.2 Energy Storage in Transport and Greenhouse Gas Emissions.....	8
1.6 Environmental and Regulatory issues for Energy Storage.....	8
2. Inventory of Energy Storage Technologies	11
2.1 Advanced Battery Systems.....	11
2.1.1 Supercapacitors	11
2.1.2 Nickel Batteries.....	12
2.1.3 Lithium Batteries	12
2.1.4 Lead-Acid Batteries	14
2.1.5 Flow Batteries	14
2.1.6 Metal-Air Batteries	16
2.1.7 Sodium-Sulphur Batteries.....	17
2.2 Fluid Storage	19
2.2.1 Pumped Hydro-Electric	19
2.2.2 Compressed Air Energy Systems (CAES).....	19
2.3 Mechanical Systems	20
2.3.1 Flywheels	20
2.4 Electro-Magnetic Systems.....	22
2.4.1 Superconducting Magnet Energy Storage (SMES)	22
2.5 Transport Systems	23
2.6 Hydrogen for Energy Storage.....	23
2.6.1 Hydrogen for Electricity Transmission and Distribution.....	23
2.6.2 Hydrogen for Transport and Mobility.....	25
2.7 Summary	27
3. Research and Development Programmes.....	31
3.1 European Research	31
3.2 International Energy Agency.....	32
3.3 Conclusion.....	33

4. Promising Emerging Technologies.....	34
4.1 Introduction	34
4.1.1 Power Quality	34
4.1.2 Energy Management	35
4.1.3 Transport and Mobility	36
5. Policy Challenges	38
5.1.1 Energy Security.....	38
5.1.2 Achieving RES Targets - Intermittent renewable sources and storage...38	38
5.1.3 Regulation of the Energy market	41
5.1.4 The Influence of Renewable Energy Support Mechanisms.....	43
6. Policy Conclusions and Recommendations	45
6.1 Conclusions	45
6.2 Recommendations	45
Annex 1 – Gas Storage.....	47
Bibliography	51
GLOSSARY	54
ABBREVIATIONS.....	56

EXECUTIVE SUMMARY

This report provides an overview of the current status and outlook for energy storage technologies.

Section 1 introduces energy storage and sets out the scope of this study. It also discusses some of the potential applications of the different technologies and reviews briefly some of the economic and environmental issues arising from their deployment. Section 2 sets out an inventory of energy storage technologies, showing how these technologies fall into a number of different technical types. This section also provides a summary of the characteristics of the technologies and their advantages and drawbacks. Section 3 provides a brief summary of the main international research programmes and activities that are in place to support the development of these technologies. Section 4 reviews the most promising technologies for the main potential applications. Section 5 considers the policy challenges relevant to the deployment of energy storage technologies, to help in the development of appropriate recommendations. Section 6 sets out a number of appropriate recommendations.

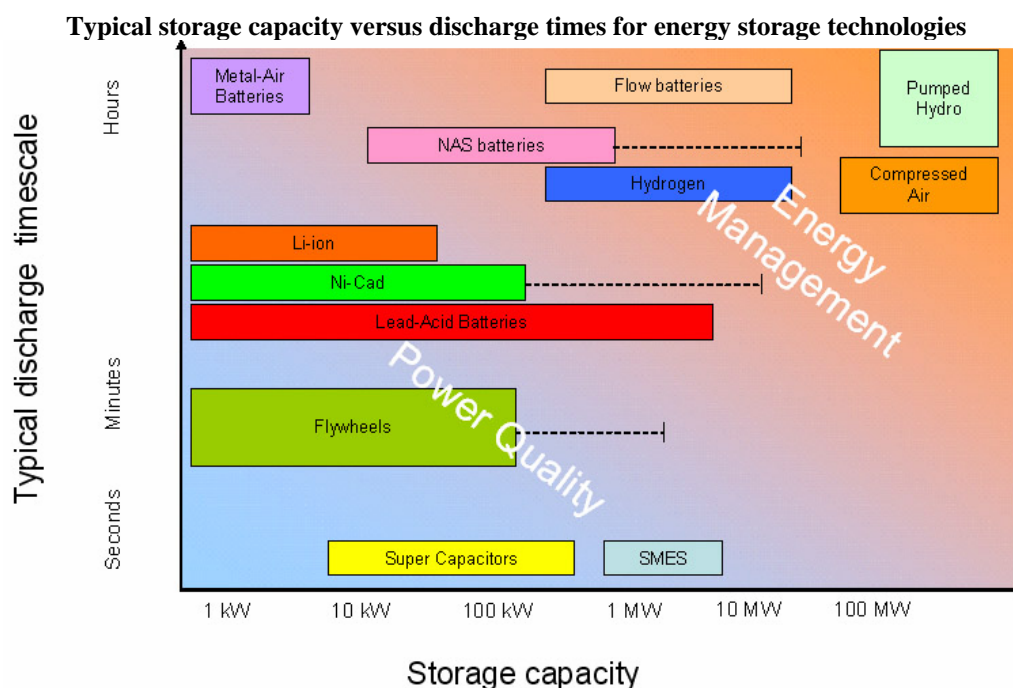
Annex 1, sets out some of the current context surrounding the issue of gas storage.

Energy Storage

EU energy policies have clearly identified energy storage technologies as an area to be pursued further, given their potential contribution to energy security and greenhouse gas emissions reductions. This report considers how energy storage technologies can contribute to two key areas of opportunity, within the:

- Electricity Transmission and Distribution sector; and
- Transport sector.

For the electricity transmission and distribution sector, energy storage might assist power quality applications, energy management applications or both, as shown in the diagram below.



(Figure adapted from: Electricity Storage Association.

http://www.electricitystorage.org/tech/technologies_comparisons_ratings.htm)

The economics of energy storage applications vary widely. Within the electricity transmission and distribution sector, *the structure of electricity markets and the way they are operated and regulated is a key issue in determining the value and economics of energy storage*. For transport applications, some technology applications are already cost-effective.

Carbon savings arising from the utilisation of energy storage on electricity networks will be positive but the calculation of precise carbon savings is both difficult and open to debate. Similar to the economic uncertainties described above, this is due to the very wide range of possible scenarios under which energy storage will contribute to the displacement of emissions. In the transport sector, carbon savings from energy storage technologies are positive and are somewhat more straightforward to assess. Nevertheless, a range of carbon saving possibilities exists.

Some energy storage technologies may have environmental burdens associated with them (e.g. the Cadmium content of Nickel Cadmium batteries) but in general terms these issues are not insurmountable and development of these technologies would take place within the existing framework of appropriate European environmental Directives.

Inventory of Energy Storage Technologies

This report groups energy storage technologies into the following categories, as shown in Section 2.

- Advanced Battery Systems
- Fluid Storage
- Mechanical Systems
- Electro-Magnetic Systems
- Hydrogen for Energy Storage

Section 2 discusses the technologies and provides information on their:

- Technical Performance
- Development Status
- Economics
- Environmental Impacts

A number of case study examples are used to illustrate potential applications.

Table 1 summarises all of the technologies discussed.

Research and Development Programmes

Section 3 briefly summarises the main current international research programmes on energy storage under European programmes and the International Energy Agency's work.

Promising Emerging Technologies

Using the information arising from the inventory of technologies, we have identified the most promising emerging technologies relevant to each main application. These are:

For Power Quality applications

- Flywheels
- Sodium–Sulphur Batteries
- Superconducting Magnets

For Energy Management applications

- Compressed Air Energy Systems
- Flow Batteries
- Hydrogen

For Transport applications

- Lithium-Ion Batteries
- Supercapacitors
- Hydrogen

Policy Challenges

We have reviewed the relationship between European policy challenges and the potential contribution of energy storage technologies.

Energy storage technologies will contribute to European *energy security* if they can enable the increased penetration of renewables - in particular intermittent renewables - into EU energy markets. The means by which energy storage can assist with this security is dependent upon the nature of renewables' deployment (large or small-scale schemes) and the market system under which they are deployed.

The wide deployment of *intermittent renewable energy sources* leads to a requirement for back-up sources of power, for which energy storage could be one contributory solution. The development of a range of cost-effective, flexible energy storage systems is likely to allow the delivery of the RES targets at a reduced overall cost and with enhanced network flexibility. However, network-scale energy storage does not have to be a requirement for delivering the EU renewable energy targets.

The means by which the European electricity market is *regulated* and the nature of the *electricity market* are key policy issues determining the scope for energy storage to contribute effectively to energy security and emissions reduction. Currently the European electricity market remains fragmented. The inconsistent operational and regulatory approaches, and different markets, have variable consequences for energy storage. In particular there is little incentive for energy storage to be introduced in many European electricity markets that do not yet have full liberalisation and transparency. This is also true for the different forms of *renewable energy support mechanism* across the EU.

Policy Recommendations

We suggest the following recommendations, designed to assist energy storage technologies to provide maximum benefits. These recommendations are:

For Electricity Network storage

- European research on energy storage should be more clearly focused on the key technologies (identified in Section 4 of this report) and should - where practical - take greater account of key issues related to the eventual deployment of the technologies (identified in Section 5);
- We support and endorse the Commission's proposal (COM(2007) 723 final) for a European Electricity Grid Initiative and recommend that this initiative should also be used to support a specific strand of European research which would aim to encourage integration of energy storage into electricity networks;

- Work should be undertaken to confirm possible options for the stable operation of European electricity networks with very high penetrations of renewable energy (and possibly nuclear generation) in line with the 2020 and 2050 energy targets. This work should assess the quantity of storage and/or reserve generation that would be desirable and achievable under a range of scenarios for intermittent generation and the development of European transmission systems. Active participation of utility companies in this work is highly desirable;
- In view of the
 - significant market and regulatory barriers to accessing the full value of an electrical energy storage device embedded within an electricity network;
 - possible key role for storage in enabling cost effective renewable energy exploitation; and
 - scale of the EU 2020 and 2050 energy targets;
 the EU should investigate ways of supporting and monitoring trials of demonstration network scale electricity energy storage devices to allow the benefits to be confirmed;
- Work should be conducted to assess the impact of electricity network management and regulation requirements on the future prospects for energy storage. This work could be used to
 - help guide future research and development priorities; and more importantly
 - raise awareness of energy storage's benefits and issues with network operators and regulators across the EU Member States;
- The effects of renewable energy support mechanisms on electricity energy storage should be assessed. The objectives of this study would be two-fold:
 - to develop measures that could provide confidence to those investing in storage that they will be able to realise benefit from their investment;
 - to make policy makers in renewable energy aware of the issues surrounding electricity energy storage and the influence of policy measures on the potential electricity storage market;

For Transport

- EU research support should continue to reflect the long-term goal of hydrogen-based systems for storage making a major contribution to the electricity and transport sectors;
- The wider deployment of existing BEV and HEV energy storage technologies across the EU should be monitored, and should be encouraged in Europe-wide dialogue with vehicle manufacturers.

1. ENERGY STORAGE

1.1 Introduction

On 10th January 2007, the Commission issued a Communication on a Strategy for Energy Policy for Europe comprising different sets of measures and plans to secure for the EU a sustainable energy future. In the shift towards more secure, efficient and sustainable forms of energy sources and energy use, the Commission's Communication stated that energy storage is a major concern and plays a critical role in all parts of the future energy systems.

These conclusions were reinforced in the subsequent communication published on 22 November 2007 'A European Strategic Energy Technology Plan (SET-Plan) – 'Towards a low carbon future' COM(2007) 723 final. As one of the European Industrial Initiatives in this communication the Commission propose the launching of a European Electricity Grid Initiative, which will 'focus on the development of the smart electricity system, including storage, and on the creation of a European Centre to implement a research programme for the European transmission network.' In addition, as part of the 2050 vision of moving towards complete decarbonisation of the energy system elaborated in the communication, one of the 7 key EU technology challenges for the next 10 years is identified as 'Achieve a breakthrough in the cost-efficiency of energy storage technologies'.

Finding solutions to energy storage challenges is therefore identified by the Commission as a key element for achieving the EU's energy policy objectives.

The reason for the prioritisation of **electrical energy storage** is intrinsically linked with the nature of most forms of low or zero carbon energy generation that differ fundamentally from the traditional fossil fuel dominated electricity network.

Traditional forms of electricity generation store energy on site in the form of a stock of (e.g.) coal, oil, gas, nuclear fuel or water behind a dam. An Alternating Current (A.C.) electricity grid, as used in all developed and developing countries, requires that supply and demand is always matched on a second by second basis. The key role of electricity network and transmission system operators is to have arrangements in place to ensure this requirement is always met. The consequences of grids failing to match supply and demand can be severe in terms of blackouts, loss of industry production and potential loss of life.

The traditional electricity market is therefore based on fuels sold and traded as commodities¹. that are used to generate electricity to instantaneously match supply with demand.

The low or zero carbon electricity future is necessarily different. The two prevalent forms of low and zero carbon generation are based around renewable and nuclear fuels. The former is in many cases (wind and solar being the prime examples) intermittent or variable² while the latter is generally designed to operate at a constant output.

¹ Storage has always been a fundamental component of traditional energy markets. Coal, oil and gas have always been traded within commodity markets in a manner similar to coffee, metals etc. The nature of A.C. electricity networks, as described above, has, until recently, resulted in them being treated as a special case. The move to liberalise energy markets has driven governments to reconsider this special status of electricity and it is now treated in many countries as a commodity like any other, albeit crucial to the economy of that country.

² There is some debate as to whether the sources of renewable energy such as wind and solar that continuously vary in their output should be referred to as intermittent or variable. We will use intermittent in this report to describe these types of renewables. The impact of using such sources as a significant percentage of the energy supply system is considered in terms of storage later in this report.

A future electricity system predominantly or solely supplied by renewable and nuclear energy sources will therefore find it difficult to meet the fundamental stability requirement of AC networks to constantly match supply and demand.

Electrical energy storage offers the potential to store electrical energy once generated from low and zero carbon sources and to subsequently match supply and demand as required. In so doing, electrical energy becomes a commodity similar to coal, oil and gas.

Prior to the widespread introduction of the inherently less flexible low and zero carbon technologies, electrical energy storage - in the form of pumped storage and compressed air storage plants - has been a useful system management tool for electrical system operators, operating alongside traditional (fossil-fuelled) peaking plant, spinning reserve³ etc. These technologies and services allow the networks to be managed within the required technical voltage and frequency limits to constantly meet the requirement of matching supply and demand.

In future networks, significantly larger amounts of electrical energy storage - or peaking and spinning reserve plant - will be required. The latter plant already exists, or can be adapted from current base load gas and coal fired generation⁴, and so is likely to meet the balancing requirement in the short term. However the increasing requirement to decarbonise the energy networks and the associated price of carbon is likely, in the medium to long term, to drive the market towards electrical energy storage.

Electrical energy storage also has the benefit that it can take in renewably-generated electrical energy when supply exceeds demand and store it until it is required.

In **transport markets**, the ability to store electrical energy, in a form where it can be instantaneously drawn upon to power a vehicle, will also increase in value as the carbon penalty on fossil fuelled transport grows.

The issue of **gas storage** on the other hand is essential for the improving the integration of EU's energy markets, for developing solidarity mechanisms and promoting energy security.

The increasing size of the gas market over recent years requires an increase in gas storage capacities. In particular experts estimate that in 2030 between 10 and 29 billion cubic meters of working gas volume will be required (depending on the level of strategic storage for imports from non-EU countries), in addition to the existing 40 billion cubic meters. (Platts, 2007). However, there seems to be some delays in the development of the necessary appropriate infrastructure across the EU.

The energy storage area gives rise to a number of technical terms and acronyms. We have brought these together to aid understanding and they are shown in separate Glossary and Abbreviations sections at the end of the report.

Some particularly important terms are widely used to describe the characteristics of energy storage devices. These are highlighted in the box below.

³ Please refer to the Glossary for an explanation of terms.

⁴ As generation plant moves down the merit order (set by the price it requires from the market to generate – plant requiring the lowest price is at the top of the order i.e. it gets called)

Characteristics of energy storage devices:

- **Energy Density:** The amount of energy that can be supplied from a storage technology per unit weight (measured in Watt-hours per kg, Wh/kg). In combination with the physical size and weight of the storage device, this factor defines the quantity of energy that the device can take in and deliver.
- **Discharge Time:** The period of time over which an energy storage technology releases its stored energy. This is in turn related to the power capability of the device i.e. its rating in kW or MW.
- The energy rating (expressed in kWh or MWh) is important in determining how long a device can supply energy for. The power rating is important in determining how much energy can be released in a set time. As an example a 100kWh device rated at 20kW can supply 20kW of output for 5 hours ($20 \times 5 = 100\text{kWh}$).
- Costs of energy storage devices are usually quoted in terms of cost/kWh or costs/kW. These are usually related to the application the device is aimed to satisfy. Some devices will have a high cost per kWh but relatively lower cost/kW others will be the reverse. It will depend on the application as to whether a given device is potentially economic.

1.2 Scope of this Study

In this report we focus on the forms of energy storage that have the potential to facilitate the development of a low or zero carbon society. In particular, we consider energy storage technologies that have the potential to take electrical energy, generally accepted to be the dominant energy vector of the future, and store it in a chemical, mechanical or electrical potential form for variable periods of time and then release it in a controlled manner. This could be in relation to a power grid or as the power to drive a road or rail vehicle.

This report aims to:

- Review the current “inventory” of energy storage technologies;
- Identify the challenges and possible outlook for this area;
- Draw conclusions and identify appropriate policy recommendations.
- Summarise briefly the current position within the gas storage area;

There is already a large commercial market for energy storage for *portable electrical devices*. Although some of the technologies discussed in this report (especially battery technologies) are widespread within this commercial market, the storage scale involved is typically much smaller than that which is important for the issues considered in this report. For example, the widespread use of battery power for calculators and mobile phones is unlikely to represent a new opportunity for technological advance or energy saving.

For this reason, portable energy storage is not considered specifically within this report.

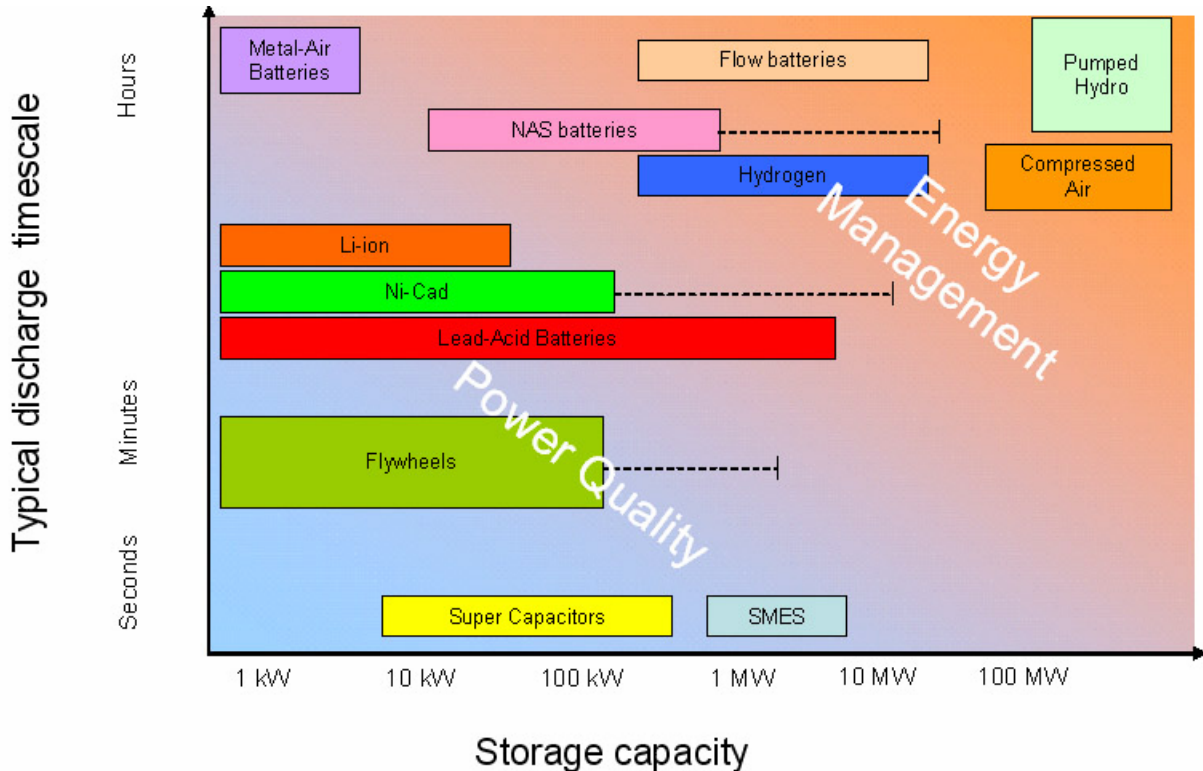
1.3 Applications of Energy Storage Technologies

As described in the previous sections, this study focuses on the forms of energy storage that can facilitate a low carbon energy system. These can be broadly divided into electricity network energy storage and transport/mobility areas. These applications are described in the sub-sections below.

1.3.1 Electricity Network Energy Storage

Electricity network energy storage technologies include devices suitable for Power Quality applications, Energy Management applications or for both purposes. Figure 1 illustrates many of these current energy storage technologies. In Figure 1, typical system power ratings for these technologies are plotted against discharge time to demonstrate their suitability for Power Quality and Energy Management.

Figure 1: Typical storage capacity versus discharge times for energy storage technologies



(Figure adapted from: Electricity Storage Association.

http://www.electricitystorage.org/tech/technologies_comparisons_ratings.htm)

Electricity energy storage technologies are important for improving the efficiency of electrical energy utilisation. The primary aims of developing and deploying electricity storage technologies is their potential to generate an “electricity reserve”, the benefits of which include:

- ***Stabilisation of the energy market:*** Areas that could see improvement with the wider application of energy storage are increased diversification and security of supply;
- ***Stabilisation of the transmission and distribution grid:*** A consequence of this is that energy management can potentially reduce the need for reserve fossil fuel plants. Power quality applications can assist in smoothing out faults and other short term disruptions and perturbations, reducing the requirement for ‘spinning reserve’ in the system. Larger scale energy storage devices could also potentially provide ‘black start capacity’;
- ***Optimisation of intermittent renewables, particularly wind:*** Linkage between intermittent sources of energy and associated storage - for example during the night or other periods of low demand - could reduce the vulnerability to supply shortages by providing a means to store excess energy, and then release it during periods of high demand. Improvements in this field will enable intermittent sources to command a higher price for the energy produced by making it more dispatchable.

Another area interlinked with mass storage is Demand Side Management (DSM) where the aim is to reduce peak demand and optimise off-peak usage. The combination of electrical energy storage and demand side measures - one operating from the supply side (storage) and the other from the demand side (DSM) - will potentially allow generation plant, both traditional and renewable, to operate in a more cost effective manner.

1.3.2 Transport and Mobility Energy Storage Applications

Energy storage appears a promising option to reduce fuel consumption, or to provide an alternative form of motive power to the gasoline-fuelled internal combustion engine. On an individual unit basis, energy storage demands in the transport sector are relatively small in comparison with the electricity sector, however, system energy density and the charge/discharge lifetime are key characteristics for promising technologies in this area.

Energy storage can be applied to the Transport and Mobility sector to yield system efficiency gains and greenhouse gas emission reductions. A number of technologies are being considered for transport purposes, including batteries, supercapacitors, hydrogen and flywheels. There is an overlap between the technologies with potential in the transport area with those in the electricity network storage area. Values listed in Table 1 for such technologies are representative of both transport scale and electricity network energy storage scale applications.

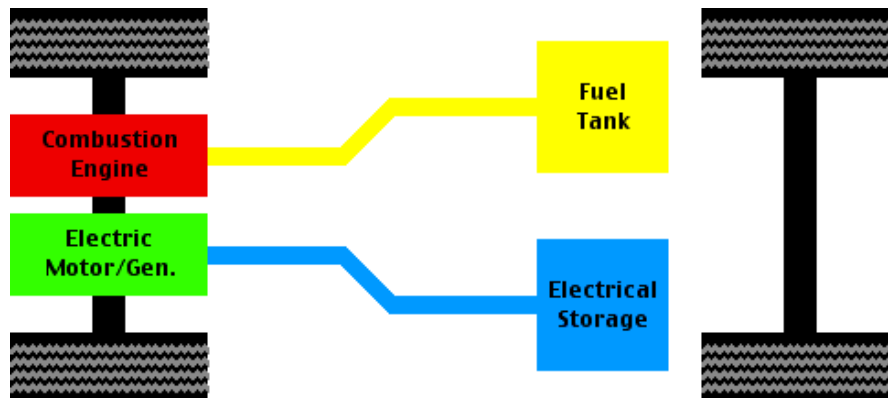
There are two types of electric vehicle currently under development, Battery Electric Vehicles (BEVs) and Hybrid Battery Electric Vehicles (HEVs).

BEVs are powered either by a large electric motor connected to a transmission, or smaller electric motors housed in the wheel hubs. The energy used to power these motors comes exclusively from battery packs housed within the vehicle that must be charged from an external source of electricity.

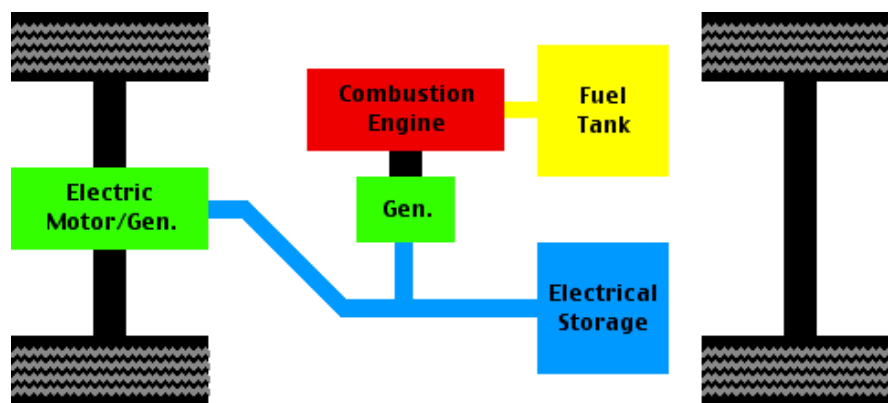
HEV technology typically combines an internal combustion engine (ICE) with an electric motor in a number of different configurations, two of the most typical are shown in Figure 2. In a parallel drive train configuration, both the ICE and electric motor provide motive power. Whereas, for a series configuration, the ICE is used solely to generate electrical energy, which is stored and used by an electric motor that provides all the motive power. The combination of an ICE with an electric motor can lead to increases in overall energy efficiency (particularly for urban applications). Vehicles operating extensively in urban areas, such as delivery vans and buses, can suffer very large energy losses due to the high proportion of decelerating and braking. Such vehicles require engines that can perform across a relatively wide range of operating conditions, and such engines are usually less efficient and bigger than engines designed to operate over a more restricted range. Hybrid technology operates to improve the overall efficiency of petrol or diesel fuel use. In HEVs, an electric motor assists in acceleration, which allows for a smaller and more efficient ICE. In addition, the engine can be stopped and started quickly to reduce stationary engine idling and hence fuel consumption. The electric motor can recover energy from braking, referred to as regenerative braking. Surplus power from the ICE is used to generate electricity, or in a series hybrid, the ICE is used solely for generating electricity with the electric motor providing all of the motive power.

Fig 2: Typical hybrid electric vehicle drive train configurations

Parallel drivetrain configuration



Series drivetrain configuration



Source: <http://www.altfuels.org/backgrnd/altdrive.html>

1.4 Economics of Energy Storage

The economics of a given energy storage device or technology are very dependent on its application and the structure of the market. For this reason we have provided in the following Section indicative costs for the technologies - however the economics of a given device can only be assessed in the context of a specific application. There are very limited examples of these at the current time for most technologies. Where they are available we have referenced them.

1.4.1 Economics - electricity network energy storage

A recent report (SEI, 2007), has examined the economics of a 2MW, 12 MWh redox flow battery system linked to a 6MW windfarm in Ireland. The objective of linking the windfarm and energy store is to improve the revenue opportunities for the windfarm. This report provides a good example of the range of issues that need to be included in an economic analysis of this type of application, the potential revenue streams and the risks involved. It also highlights the fact that the economics would be quite different in other countries and under different market regimes.

For example, when the NETA (New Electricity Trading Arrangements) were introduced in England and Wales in 2001 the pumped hydro-electric storage units at Dinorwig and Ffestiniog in Wales were initially able to realise very high incomes, as within the NETA market the system sell and buy prices showed large spreads.

The regulator and government recognised this and the consequences it had for other market players (such as wind farms) and for the operation of the market. Steps were taken to reduce the price spread – the result was a much reduced demand and value for storage. At least one of the plants has spent periods out of service in more recent times.

This points to a general conclusion for the development of energy storage technologies in grid applications; ***the structure of electricity markets and the way they are operated and regulated is a key issue in determining the value and economics of energy storage.*** This in turn results in a political/regulatory risk for any developer or financier of an energy storage device.

This is discussed in more detail later in this report (see Section 5) and must be recognised as a significant issue in the development of future roles for energy storage. This relates especially to energy storage's potential role in enabling the widespread deployment of intermittent or variable renewables in electricity generation and supply.

1.4.2 Economics – battery electric vehicles

BEVs typically use 0.12 to 0.3 kWh of energy per km (INL, 2007). Therefore for a range of 100 km at 0.2 kWh/km, a battery capacity of 20 kWh will be required. Taking energy densities of 50 and 100 Wh/kg, which fall into the mid-range of Nickel batteries, results in a battery that weighs 200 to 400 kg. Assuming an average energy consumption of 8 litres/km for a petrol engine vehicle which is equivalent to about 0.5 kWh/km, BEVs are already more energy efficient than conventional petrol-fuelled vehicles.

1.5 Energy Storage and Greenhouse Gas Emissions

As shown in Figure 1 and in the following inventory Section, there is a diverse range of energy storage technologies, many of which are suited to a specific application. There is great potential to reduce overall greenhouse gas emissions through the introduction of storage technologies. In addition, numerous approaches could be taken to implement energy storage technologies with each leading to a different potential greenhouse gas emission reduction.

1.5.1 Electricity Network Energy Storage and Greenhouse Gas Emissions

Energy storage technologies applied in electricity networks can be used to:

- Reduce or remove the requirement for the spinning reserve usually provided by conventional fossil fuel fired power stations that is necessary to operate the electricity grid in a stable manner;
- Directly link to intermittent or variable renewable energy power generation plant and increase the value of the output, by allowing it to be sold when the value is highest rather than when it is generated;
- Directly reduce the output - and hence the emissions - of fossil fuel fired power stations through storing surplus electricity at times of low demand and subsequently providing output at times of high demand, avoiding the use of peaking plant that is often fossil-fuelled.

These options lead to different greenhouse gas savings. For example the greenhouse gas reduction potential of an electricity storage device embedded within an electricity distribution network would be dependent on the carbon intensity of the generators connected to that network. This could vary with time, the store replacing output from a coal plant or alternatively a gas turbine.

The greenhouse gases displaced would be different in each case. In the case of a storage device that is removing the requirement for a coal fired plant to be operated in spinning reserve mode, the carbon displaced could be as high as 0.25 tC/MWh. If the storage is assumed to displace carbon at the average carbon intensity of the UK grid in 2005 the carbon saving would be 0.12 tC/MWh. If the storage is displacing modern gas fired combined cycle plant the displaced carbon would fall to 0.05 tC/MWh.

The above carbon savings all assume that the storage is being supplied from a carbon-free generation source such as wind. If the store was embedded within a network, remote from a generator, it could be argued that the store was supplied by electricity that would have the carbon intensity of the combination of plant operating on the network at the time of storage. The plant would, as above, upon discharge displace peaking plant, assuming this was coal fired plant the carbon saving would be 0.25 – 0.12 tC/MWh, i.e. of the order of 0.13 tC/MWh.

Existing peaking plant (gas, oil and coal fired) will be the first option for providing peaking capacity as additional renewable energy is added to the system. Its replacement by the low and zero carbon technologies discussed in this report will be dependent on, *inter alia*, future fossil fuel costs, the cost of carbon, the effects of regulation and the availability of investment funds.

The conclusion from the above assessment is that the carbon savings from the utilisation of storage on electricity networks will be positive but the calculation of precise carbon savings is both difficult and open to debate. In addition, as the overall network is increasingly decarbonised the carbon savings from operating storage will decrease; however the marginal savings i.e. the potential for storage to displace the most carbon intense plant remaining on the network (fossil fuelled peaking plant) will increase.

1.5.2 Energy Storage in Transport and Greenhouse Gas Emissions

The economics of energy storage devices in the transport area are based on their use to replace petrol or diesel powered vehicles with either hybrid vehicles (HEV), which use an electric motor in combination with a petrol or diesel, or a battery electric vehicle (BEV). Work by AEA Energy & Environment (AEA, 2008 - to be published) indicates that the carbon savings per year on switching from a petrol or diesel engine vehicle (private car) to a BEV are of the order of 44% for the petrol vehicle and 40% for the diesel. The absolute carbon emissions per year for vehicles depend on a wide range of factors, *inter alia*, engine capacity, type of use, mileage, driving style and maintenance regime. A typical value for emissions would be 0.5 to 1.5 tonnes of carbon per vehicle per year (private car). On this basis the carbon savings would be of the order of 0.2 to 0.6 tonnes of carbon per year per vehicle (private car).

For a typical HEV (such as a delivery van) the savings would be of the order of 20% on typical annual carbon emissions of the order of 3 tonnes, i.e. 0.6 tonnes of carbon per year. It should be noted that the assessment for SEI includes the whole life carbon impact of the different vehicle types, the production and disposal carbon impact of the HEV and BEVs are twice that for fossil fuelled powered vehicles. This is associated with increased production complexity and battery disposal costs. The margin is likely to decrease as BEVs and HEVs production levels increase.

1.6 Environmental and Regulatory issues for Energy Storage

There are a large number of energy storage devices described in this report. Depending on the specific device or technology in question, there are a number of European Directives that may be applicable to the development, construction, use and disposal of the energy storage devices.

Below is a summary of the main European Directives that may be applicable to energy storage devices (although depending on the devices in question other Directives may also be applicable). It should be borne in mind that only certain aspects of particular energy storage devices may present additional environmental or regulatory burdens – for example batteries containing cadmium.

The first set of Directives are those with the purpose of creating a single market for electrical goods throughout Europe by providing common safety standards for equipment. This allows a European-wide structure whereby goods can be manufactured and sold across Europe without the need for approval by individual countries. These may need to be taken into account when developing the different types of energy storage devices.

The Simple Pressure Vessels Directive (87/404/EEC) is aimed at vessels intended to contain air or nitrogen within certain parameters relating to design pressure and product size. It covers most pressure containers for air, although the scope is strictly defined. Where this directive is not applicable *The Pressure Equipment Directive (97/23/EC)* will more than likely apply instead.

Either of these directives could be applicable to compressed air energy storage systems.

The *Low Voltage Directive (2006/95/EC)* sets out requirements for the manufacture of electrical equipment. Essentially the equipment is required to be safe and this is defined by the specifications outlined in the Directive.

The Electromagnetic Compatibility Directive (2004/108/EC) also has the purpose of the creation of a single market for electrical goods throughout Europe. However unlike those outlined above the primary purpose of this directive is not the safety of equipment, but the protection of the electromagnetic spectrum. Again some of the energy storage devices described in this report may need to take this directive into account e.g. super-conducting magnets.

The second set of Directives are those aimed at restricting the use of certain substances and waste management issues for energy storage devices at the end of their life.

Batteries make up a large proportion of the energy storage devices discussed in the report. These are covered by the *Directive on Batteries and Accumulators and Waste Batteries and Accumulators (2006/66/EC)*, which was adopted in September 2006. This Directive prohibits the placing on the market of batteries and accumulators with a proportional mercury or cadmium content above a fixed threshold. This will have an impact on the future use of Ni-Cd batteries, which will be superseded by other battery types.

The Batteries Directive aims to make businesses that produce and sell batteries responsible for collecting and recycling spent batteries and requires all batteries placed on the market to be collected and recycled (with limited exceptions) and prevent their disposal by landfill/incineration. Collection rates and recycling targets are also set out within the Directive.

The recycling capabilities in some countries are limited to certain battery types and others may need to be stored and shipped to countries where suitable recycling plants exist. This has the potential for storage issues for spent batteries at the end of their life.

For example, in the UK recycling plants for Ni-Cd batteries do not exist and 25 tonnes are required before it is viable to ship them to countries such as France where suitable recycling facilities exist⁵.

⁵ http://www.wrap.org.uk/local_authorities/batteries/battery_recycling_information/qa_collection.html

With the declining use of Ni-Cd batteries it is unlikely that a significant number of recycling plants capable of dealing with these batteries will be developed, however this may lead to storage issues in the short term until they disappear from the market.

The *Waste Electronic and Electrical Equipment (WEEE) Directive (2002/96/EC)* and the *End-of-Life Vehicles (ELV) Directive (2000/53/EC)* require batteries to be removed from waste electronic and electrical equipment and end-of life vehicles respectively.

These directives help reach recycling targets, by requiring the removal of batteries and appropriate recovery. For example in the UK, approximately 90%⁶ of lead acid batteries from vehicles are recycled.

Note that the *Restriction on the use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) Directive (2002/95/EC)*, which restricts the use of substances such as mercury, cadmium, lead, chromium VI, PBB and PBDE does not apply to batteries in electrical and electronic equipment. The Batteries Directive covers this separately.

Depending on the configuration of the energy storage device the WEEE and RoHS Directives may be applicable with respect to monitoring and control instruments e.g. thermostats/control panels.

Other directives such as the *Waste Framework Directive (75/442/EEC)* and the *Hazardous Waste Directive (91/689/EEC)* will also be applicable, depending on the hazardous/non-hazardous classification of the energy storage devices when discarded at the end of their life, should the waste stream not already be covered by some of the Directives outlined above.

⁶ <http://www.letsrecycle.com/equipment/batteries.jsp>;
<http://www.wasteonline.org.uk/resources/InformationSheets/Batteries.htm>

2. INVENTORY OF ENERGY STORAGE TECHNOLOGIES

The inventory of technologies discussed in this Section has been divided into a number of technology categories. Each of these technologies may be suitable for different kinds of applications (for example, Power Quality, Energy Management or Transport). The characteristics of each of the technologies and their possible applications are summarised in Table 1.

2.1 Advanced Battery Systems

2.1.1 Supercapacitors

Technical summary: Supercapacitors can store energy in the electric field between a pair of charged plates. Supercapacitors, ultracapacitors or double-layer capacitors (DLCs) as they are also known, contain a significantly enlarged electrode surface area compared to conventional capacitors, as well as a liquid electrolyte and a polymer membrane.

Energy Density and Discharge Time: Supercapacitors are capable of very fast charging and discharging times, and are able to go through many cycles without degradation. Energy densities up to 5 Wh/kg were reported for supercapacitors by the 5th Framework INVESTIRE Network report (Willer, 2003). Recent research undertaken at the Massachusetts Institute of Technology into a novel ultracapacitor, reports a characteristic energy density of greater than 60 Wh/kg and a lifetime longer than 300,000 cycles (LEES, 2007).

Energy Efficiency: Typical efficiencies for supercapacitors are high (85 – 98%) (Willer, 2003) making them an attractive storage technology for many applications, however currently these are mostly small-scale.

Development/Deployment status: Supercapacitors were discovered in the mid 20th century and have been marketed since the 1980s. Interest has grown as their energy storage capacity has increased. Supercapacitors found their first application in military projects — for example, starting the engines of battle tanks and submarines or replacing batteries in missiles. Common applications today include starting diesel trucks and railroad locomotives, actuators, and in electric/hybrid-electric vehicles for transient load levelling and regenerating the energy of braking. NASA has used 30 large supercapacitors in its turbo-electric city bus.

Application: Honda has developed a high-performance ultra-capacitor to serve as a supplementary power source to the FCX hydrogen fuel cell (Honda, 2007).

Economics: In 2005, the ultracapacitor market was between US \$272 million and \$400 million, and is growing, especially in the automotive sector (IEEE, 2007). The economic cost of a supercapacitors in 2002 were listed as 200 to 1000 €/kW (INVESTIRE, 2003).

Environmental Impacts & Regulatory Issues: Supercapacitors can be employed to enhance the energy performance of automotives, for example, through regenerative braking systems, which can therefore lead to emissions benefits. In addition, supercapacitors have a long life-cycle. Potential negative environmental impacts of supercapacitors arise from the materials and compounds used within their construction and operation. The use and eventual disposal of materials within supercapacitors will be influenced by relevant legislation (Section 1.6).

2.1.2 Nickel Batteries

Technical summary: In common with other advanced battery systems, Nickel batteries are electrochemical cells. There are a number of Nickel based batteries currently available or under development, including Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH), Nickel-Zinc (Ni-Zn) and Sodium-Nickel Chloride (Na-NiCl₂). Ni-Cd and Ni-MH are the most developed of the Ni batteries.

Energy Density & Discharge Time: These various Ni battery types cover the energy density range 20 – 120 Wh/kg (Dahlen, 2003). The lifetime of batteries is determined by the number of charge/discharge cycles that they can perform. Ni-Cd and Ni-MH batteries perform among the highest number of deep cycles relative to other battery technologies, typically up to around 1500 deep cycles. Ni-Zn and Na-NiCl₂ have a shorter lifetime. Ni-Cd batteries also have a strong memory effect, where as in Ni-MH batteries the effect is much less significant.

Energy Efficiency: Ni-Cd and Ni-MH batteries are the most developed of the Nickel batteries. However, they also offer the lowest efficiency, discharging around 70% of the energy used during charging, although Ni-Cd batteries have a lower self-discharge rate than Ni-MH. In comparison, Ni-Zn batteries offer efficiencies of ~80% and Na-NiCl₂ batteries have an efficiency of around 90%.

Development/Deployment status: Ni-Cd batteries have been produced since the early 20th century and formed the majority of the rechargeable battery market in consumer electronics by the 1990s. The first consumer Ni-MH batteries appeared in the 1980s and have replaced Ni-Cd in many rechargeable battery applications. Despite being used widely in electric vehicles, there are few examples of their application to electricity markets.

Applications: the Golden Valley Electric Association (GVEA) in Fairbanks, Alaska installed a large-scale Ni-Cd Battery Energy Storage System (BESS) to provide 27 MW of electricity for a minimum of 15 minutes to stabilise the local power grid in the event of sudden loss of generation. The BESS was designed and built by Saft, an international battery manufacturer, and comprises 13,760 Saft SBH 920 high-performance rechargeable Ni-Cd cells arranged in four parallel strings. The system provides a nominal voltage of 5,000 V and a storage capacity of 3,680 Ah. At the time, the BESS was awarded the Guinness World Record for ‘the world’s most powerful battery’ by delivering 46 MW for 5 minutes.

Economics: Both Ni-Cd and Ni-MH batteries are expensive to manufacture relative to other battery technologies, possibly twice the cost of Lithium batteries and potentially four times the cost of lead acid batteries. The GVEA BESS discussed above was developed in 2005 at a cost of US\$ 30-million.

Environmental Impacts & Regulatory Issues: The most significant drawback of Ni-Cd batteries is the highly toxic cadmium used within them. Although this metal is highly recyclable it is exceedingly toxic. Most Nickel is recovered from end-of-life batteries since the metal is reasonably easy to retrieve from scrap and can be used in corrosion resistant alloys such as stainless steel. EU legislation is in part responsible for the supercedence of Ni-Cd batteries by Ni-MH batteries and represents a significant issue to any future development of Ni-Cd battery technologies.

2.1.3 Lithium Batteries

Technical summary: In common with other advanced battery systems, Lithium batteries are electrochemical cells. Lithium-Ion (Li-ion) and Lithium-Polymer (Li-pol) types are both available.

Energy Density & Discharge Time: Li-ion and Li-pol batteries offer high charge densities of 100 – 150 Wh/kg (INVESTIRE, 2003). Nanocomposite electrode systems may offer even higher energy densities.

Energy Efficiency: Charge/discharge efficiencies of 90 – 100% are reported for Lithium batteries.

Development/Deployment status: Li-ion batteries have taken over 50% of the small portable market in the last few years, however there are some challenges for making large-scale Li-ion batteries.

Under the EU 6th Framework Programme a consortium of European organisations is investigating advanced lithium energy storage systems based on the use of nano-powders and nano-composite electrodes/electrolytes. According to a 2004 report from the Taiwanese Industrial Technology and Research Institute (ITRI, 2004) their nanocomposite electrode technologies can provide energy densities of greater than 200 Wh/kg.

Applications: In the US the Department of Energy has sponsored a project by SAFT and SatCon Power Systems to design and construct two 100 kW / 1 minute Li-ion battery energy storage systems for use in providing power quality for grid connected micro-turbines (Figure 2). The units were tested at two utility partner sites, one at Southern Company Services and the other at American Electric Power (Oweis, S. et al, 2003). The automotive industry is driving much of the development in Li battery technology with, for example, the Tesla roadster battery system utilising Li batteries. The Tesla system is comprised of 6800 small Li-ion cells and is rated to provide around 200 kW electrical power (Berdichevsky G. et al, 2006).

Economics: According to the Energy Storage Association (ESA, 2007) the main hurdle associated with mass energy storage systems using Li batteries is the high cost (above €420/kWh) due to special packaging and internal overcharge protection circuits. Several companies are working to reduce the manufacturing cost of Li-ion batteries to capture large energy markets (multi-kW, kWh sizes for residential & commercial markets). The automotive industry is one of the main drivers behind this development.

Environmental Impacts & Regulatory Issues: Li batteries have a limited environmental impact since the lithium oxides and salts can be recycled.

Figure 3: A 100 kW Li-ion energy storage system



Source: Saft America

2.1.4 Lead-Acid Batteries

Technical summary: In common with other advanced battery systems, Lead-Acid batteries are electrochemical cells, in this case based upon chemical reactions involving lead and sulphuric acid. Lead-Acid is one of the oldest and most developed battery technologies.

Energy Density & Discharge Time: Because of the high density of the materials used in these batteries, the typical energy densities are lower than other batteries at 25 – 45 Wh/kg.

Energy Efficiency: Charge/discharge efficiencies for lead-acid batteries are 60 – 95% with self-discharge rates of 2 to 5% per month (Lailler, 2003).

Development/deployment status: In stationary storage applications, energy density is typically of less importance and lead acid battery energy storage systems have traditionally dominated this market, partly due to their low cost. Some examples of large-scale lead acid battery energy storage systems are summarised below.

Applications:

- The 8.5 MWh BEWAG plant in Berlin, was constructed in 1986 when West Berlin was essentially an 'electrical island' in the East. The BEWAG system provided a crucial spinning reserve and frequency regulation functionality.
- The 5 MWh Vernon Plant at Exide Technologies' lead-acid battery recycling facility in California. The \$4 million system was installed in 1996 and serves primarily as an Uninterruptable Power Supply (UPS). If the recycling facility loses utility power, the battery energy storage system instantly provides up to 5 MW of power to support critical infrastructure. If necessary, the system can operate the whole plant for up to one hour. The system is also used for peak shaving.
- The 1.4 MWh Metlakatle plant installed in 1997 and operated by Metlakatla Power and Light. The system was used to condition the hydroelectric current that powers a sawmill in a rural island community. Although the sawmill has now closed, prior to the installation of the battery storage system, the sawmill operators transported diesel fuel by boat to the island to run a back-up generator. During the course of its operation, the battery storage system saved close to 90% of the mill's annual energy costs.

Economics: Lead acid batteries are low cost compared to other battery technologies, being as much as 8 times less expensive than Li batteries and up to 13 times less than Ni batteries. The cost in 1995 prices of the BEWAG and Vernon installations discussed above were 707 and 305 \$/kWh respectively.

Environmental Impacts & Regulatory Issues: The lead used in these batteries is toxic and therefore must be recycled. In addition, the sulphuric acid typically used as the electrolyte is corrosive and when overcharged the battery generates hydrogen which presents an explosion risk. Under Directive 2006/66/EC, a minimum recycling rate of 65% by average weight of lead acid batteries must be reached in EU Member States by September 2011.

2.1.5 Flow Batteries

Technical summary: Flow batteries store and release energy through a reversible electrochemical reaction between two electrolytes. There are four types of flow battery currently being produced or in the late stages of development; zinc bromine, vanadium redox (VRB), polysulphide bromide and cerium zinc. The zinc-bromine system - developed by ZBB Energy Corp in the USA - represents a type of hybrid flow battery. A leading form of the vanadium redox flow battery is a system by VRB Power Systems Inc in Canada.

These systems feature the separation of chemical reactants from the electrochemical cells through which charging and discharging take place. The storage capacity is dependent upon the size of the electrolyte tanks whilst the power output is dependent upon the size of the fuel cell. The vanadium redox system has an advantage over the hybrid system as the discharge time at full power can be varied. See Case Study 1 for further technical details of the VRB system in Ireland.

Energy Density & Discharge Time: VRBs can be fully discharged without reducing life expectancy. A VRB in Sapporo, Japan has undergone around 14,000 discharge cycles, this gives it a competitive advantage over many other storage technologies (Holzman, 2007).

Energy Efficiency: These systems have quoted efficiencies varying from 70% (cerium zinc) to 85% (vanadium redox) (Baxter (2006)).

Development/Deployment status: The VRB system is currently being deployed at a number of wind farms around the world. A case study of Sorne Wind Farm in Ireland is given below. The ZBB system has been undergoing testing at the DUIT facility in the US at a 500 kWh scale, with plans to link four to make a 2 MWh battery. A report on US energy storage (UK DTI, 2006) commented that the ZBB system was the noisiest system observed and the presence of multiple pumping circuits also indicates that regular maintenance activity will be required. Whilst these technology examples are in the early stages of development it would appear that the Vanadium battery is currently the lead technology.

Economics: The overall cost of a 2MWh ZBB system would be in the region of €1.8 million. The cost of the VRB system illustrated in Case Study 1 was just over €6 million for a 2MW, 12 MWh system.

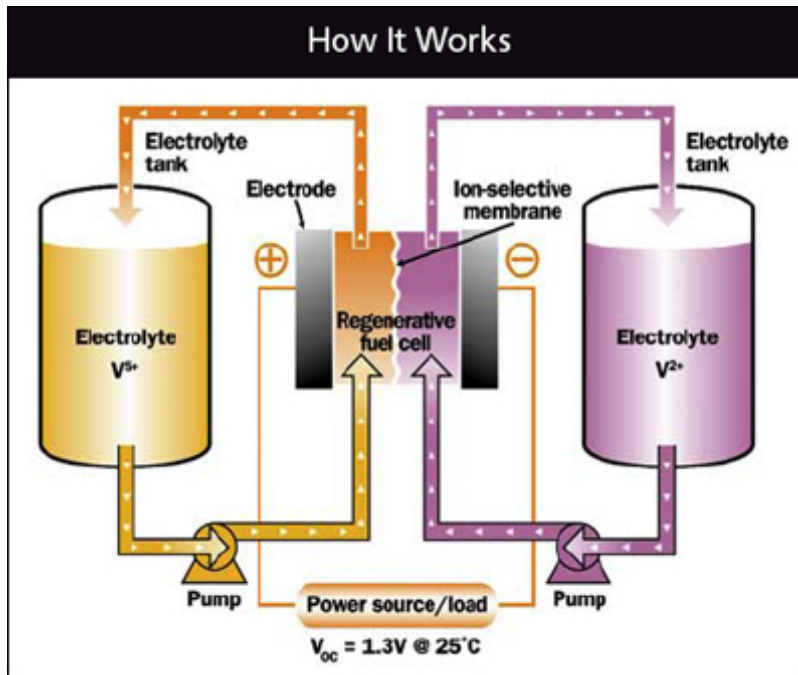
Environmental Impacts & Regulatory Issues: The potential size and scale of these systems are likely to determine the extent to which environmental impacts are significant. Significant quantities of space may be required for holding tanks containing the electrolytes and although these substances may not be specifically toxic this obviously requires care at the design stage. A major advantage of the technology is the ability of the technology to perform discharge cycles indefinitely so there are no significant waste products associated with operation.

Case Study 1: Vanadium Redox Flow Battery, Sorne Wind Farm Ireland

Location: Sorne Wind Farm, Buncrana, Donegal Ireland. The wind farm is one of the largest in Ireland with a capacity of 32 MW, with an additional 6.9MW being installed in Autumn 2007.

Technology: Vanadium redox battery system by VRB Power Systems Inc. who have been contracted to supply a 2 MW system with 12 MWh of storage. The battery comprises of two reservoirs storing two different electrolyte solutions (see Figure 4). These storage tanks feed into a regenerative fuel cell which is split by a membrane. Through pumping the differently charged electrolyte solutions to flow through the fuel cell the electron transfer between these can be diverted into an external circuit. The reverse situation is the case when charging. As such the storage capacity depends upon electrolyte concentration and the volume. The voltage is related to the number of cells in the stack. The maximum current is proportional to the surface area of the electrodes in each cell.

Purpose: The VRB system enables surplus electricity to be stored when demand is low and therefore can improve the consistency of supply from intermittent sources to the electricity network. The use of storage will enable wind farms, such as Sorne, to predict with high certainty the amount of power they can deliver for the forthcoming hours. This will result in improved asset utilisation and a higher load factor.



At present prices for generation in Ireland attain €6 MWh for conventional power whilst for wind this is €7 MWh. This difference reflects back up potential required for intermittent energy, utility providers needing to keep reserve power on standby or purchase on the spot power both of which are expensive options. The system at Some will provide 3 MW of pulse power for 10 minute periods every hour in order to combat short term volatility.

Figure 4: Diagram of Vanadium redox battery (Source: VRB Power Systems Inc)

Economics: The total cost of the VRB-ESS was assumed to be just over €6 million. The scheme will be able to generate some finance through ancillary reserve payments and capacity payments which are available to power generators in Ireland, the feasibility study undertaken has calculated the total as being €220,136 per annum. The internal rate of return (IRR) is calculated as being 17.5% as opposed to the 10% IRR typically achieved in the Irish market.

Sources: <http://www.vrbpower.com/docs/news/2007/Ireland%20Feasibility%20study%20for%20VRB-ESS%20March%202007.pdf>

Quast, C. (2007) A Study of wind power storage in Ireland; Baxter (2007); The Vanadium Advantage (2007)

<http://www.ehponline.org/members/2007/115-7/EHP115pa358PDF.pdf>

2.1.6 Metal-Air Batteries

Technical summary: In common with other advanced battery systems, metal-air batteries are electrochemical cells. Metal-air batteries are the most compact batteries available according to the Energy Storage Association (ESA, 2007).

Energy Density & Discharge Time: Energy densities for metal air batteries can be high covering the range 110 – 420 Wh/kg (Worth B. et al, 2003).

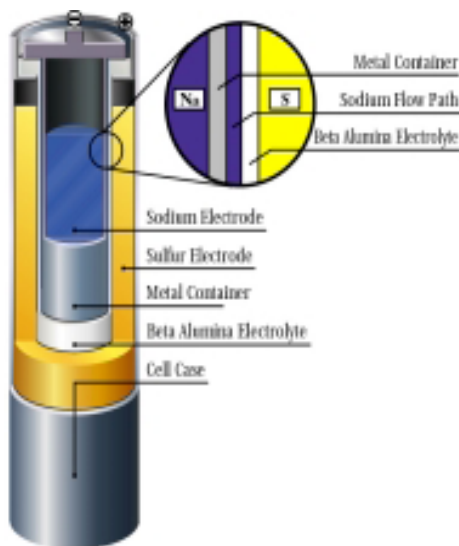
Energy Efficiency: The most significant disadvantage of metal-air batteries is the inefficient electrical recharging leading to a typical charge/discharge efficiency of around 50%.

Development/Deployment status: Of all the metal-air systems developed to date the zinc-air battery is the most advanced despite the fact that other metal electrodes have a higher theoretical energy density. The deployment of metal-air batteries is limited to small-scale applications such as hearing aids or systems in which the fuel cells are mechanically refuelled. The electrical rechargeability of these batteries needs to be improved to enable competition with other rechargeable battery technologies.

Economics: The capital costs of metal-air batteries are quoted as one of the least expensive (ESA, 2007) but this cost must be treated with caution since these batteries are very difficult and inefficient to re-charge.

Environmental Impacts & Regulatory Issues: Environmentally, metal-air batteries are relatively inert since no toxic materials are involved in their construction. In common with other battery types, metals such as zinc or aluminium used within the battery should be recycled.

2.1.7 Sodium-Sulphur Batteries



Technical summary: In common with other advanced battery systems, Sodium-Sulphur (NaS) batteries are electrochemical cells. NaS batteries are the most developed type of high temperature battery. A NaS battery consists of liquid (molten) sulphur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte (Figure 5). The electrolyte allows only the positive sodium ions to pass through it and combine with the sulphur to form sodium polysulphides.

Energy Density & Discharge Time: NaS batteries have a relatively high energy density, within the range 150 – 240 Wh/kg (DTI, 2004). NaS has significant potential to become a cost-effective, modular, and portable bulk storage medium as it is specifically designed for long discharge cycles (8 hours), but has the capacity to discharge very rapidly and at multiples of

rated power.

Figure 5: NaS cell structure

Energy Efficiency: These batteries have an estimated lifetime of 15 years with a cycle life of 2500 – 4500 and charge/discharge efficiencies up to 90%.

Development/deployment status: Research and development into NaS batteries has been pioneered in Japan since 1983 by the Tokyo Electric Power Corporation (TEPCO) and NGK. As of 2004 there were 59 NaS energy storage systems with capacities rated greater than 500 kW (Mears, 2005). In total more than 100 MW of NaS energy storage capacity has been installed, mostly in Japan where this energy storage technology is a commercial reality.

Applications:

- Two systems in Japan rated at 9.6 MW and capable of delivering 64 MWh are in operation at a water treatment plant and at a Hitachi automotive plant. A further scheme due to open in March 2008 will contain 34 MW of NaS batteries. This will be in conjunction with a 51 MW wind farm at Rokkasho village (Baxter, 2007).

- American Electric Power (AEP) conducted the first grid-connected demonstration of sodium sulphur technology in the USA. The project commenced in 2002 and in collaboration with Electric Power Research Institute, the US Department of Energy, TEPCO, NGK and ABB. The system is rated at 100 kW for peak shaving or load levelling over about seven hours and up to 500 kW for short term power quality mitigation. In September 2007 AEP ordered three new NaS battery installations that together will total 6 MW and will be installed in West Virginia and Ohio.

Economics: AEP anticipate the combined cost for the three installations ordered in 2007, including site preparation, equipment and control systems, will be around \$27 million (€18.9 million). A study of the 2002 NaS demonstration project carried out for the US Department of Energy energy storage program calculated a potential 9.8% rate of return on investment in the system and suggested the present value of power quality benefits were over three times the present value of peak shaving benefits (Norris B et al., 2007).

Environmental Impacts & Regulatory Issues: There are limited environmental concerns associated with NaS batteries, since the materials used in their construction are relatively environmentally inert. There is a small risk associated with the high temperature at which the battery must be operated in order to maintain the sulphur in its molten form.

Case Study 2: Sodium-Sulphur Battery Energy Storage System

Location: Long Island bus depot, New York

In this collaborative deployment project, a 1 MW, 7.2 MWh NaS battery has been installed at a Long Island bus depot facility to shift compressor peak load to off-peak capacity and provide emergency backup power. The primary application is to supply up to 1 MW of power to a natural gas compressor for six to eight hours per day, seven days per week, especially during the summer peak period. The natural gas compressor provides fuel for compressed natural gas buses that will replace diesel-powered buses. The system will power the compressors during the day and recharge from the grid at night when utility rates are lower. The system consists of two sets of ten 50 kW NaS modules, which are connected to the AC grid through a power conversion system.

The project cost around \$ 4 million and was co-funded by the New York State Energy Research and Development Agency (NYSERDA), the US Department of Energy, the Electric Power Research Institute (EPRI) and the New York Power Authority.

An extensive monitoring and data collection system is in place to evaluate system performance, validate operating characteristics in the US and develop economic models for value-added applications. The system was commissioned in the third quarter of 2006 and the field trial of the system is expected to complete mid-way through 2008. The trial will enable a long term evaluation of the NaS battery in the areas of availability and reliability, system maintainability and charge/discharge efficiency. The estimated system efficiency in November 2006 was 75%.

Sources: EPRI (2006); Kishinevsky (2006)

2.2 Fluid Storage

2.2.1 Pumped Hydro-Electric

Technical summary: Pumped hydro-electric storage is the oldest and largest of all commercially available energy storage technologies. These schemes consist of two large reservoirs at different levels with a store of water. Off-peak electricity is used to pump water up to the top reservoir, which can then be discharged as required, typically to a lower reservoir at the other end of a height differential. This flow of water drives turbines in the same way as hydro-electric dams.

Energy Density & Discharge Time: The technology can provide reliable power at short notice, typically within 1 minute.

Energy Efficiency: The efficiency of pumped hydro is in the range of 70-85%.

Development/Deployment status: Overall the technology is one of the most mature on the market and further technological advances are thought to be unlikely. Pumped hydro is the main form of energy storage worldwide and has been used since the 1890's.

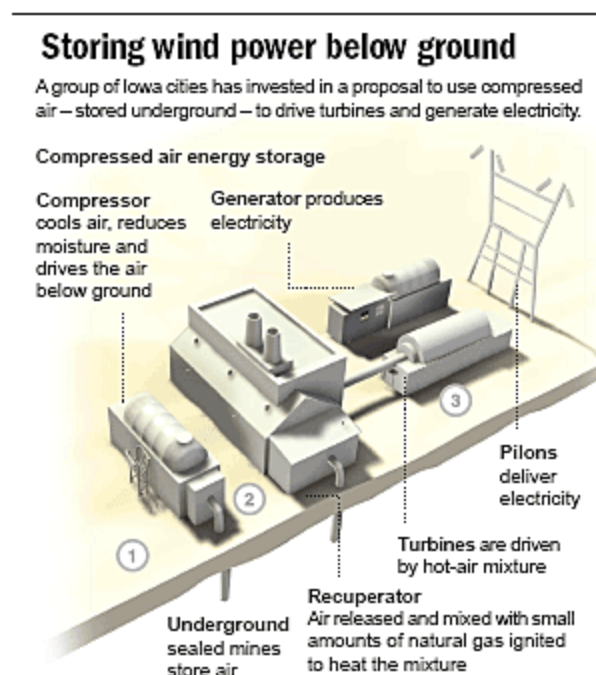
There is approximately 90GW of pumped storage in operation worldwide accounting for 3% of global generation capacity (ESA, 2007). Future advances are likely to be in the location of this technology. In Japan research is being undertaken using the concept at the coast whilst it is also theoretically possible to use old mineshafts.

Economics: A limiting factor to pumped hydro is the large capital costs involved in construction (although cost is highly dependent on local topography and other factors). For example, the 1080 MW Goldisthal plant in Germany cost \$700 million in 2002 (ESA, 2007).

Environmental Impacts & Regulatory Issues: Potential sites are limited due to the direct environmental damage caused by construction of these schemes. Using old mineshafts or coastal locations may present opportunities at locations previously not considered. Many suitable areas for potential schemes carry heightened environmental risks for ecosystems and fragile highland areas, which may often be located within National Parks.

2.2.2 Compressed Air Energy Systems (CAES)

Technical summary: This technology is a variation on a gas turbine power plant, in which air is compressed into underground mines or caverns and this store is used to improve the efficiency of the gas turbine. When required, the compressed air is utilised in conjunction with a gas turbine to generate electricity, resulting in gas consumption reductions of 60% relative to generating the same amount of electricity directly from gas. One feature of a new generation of proposed CAES plants is that they may be closely integrated with wind farms, representing a means of storing additional power generated off peak.



SOURCE: Imperial College

AP

Energy Density & Discharge Time: Since CAES is not a simple energy storage system like batteries these concepts have less applicability to the technology.

Energy Efficiency: A figure of 80% is quoted for the Alabama plant outlined below.

Development/Deployment status: This is a mature technology although there are currently only two commercial plants in operation worldwide. A number of new plants are under consideration.

Economics: The cost of the most up-to-date plant in Alabama is 400€/kWh.

Environmental Impacts and Regulatory Issues: The availability or generation of large underground storage space can potentially have environmental impacts. A constraint on this technology is the presence of suitable locations for underground air storage. For example, in the UK all suitable underground stores are presently used for gas storage.

Large scale underground stores required for schemes of this kind will have to compete with the need for storage space associated with large-scale Carbon Capture and Storage from – e.g. – coal-fired electricity generation.

Applications:

- The world's first CAES plant was constructed in 1978 at Hundorf, Germany with a rating of 290MW. The second plant is in Alabama, USA, for which construction took 30 months with a cost \$65 million (ESA, 2007).
- A possible new scheme - the Iowa Stored Energy Plant - has obtained grant funding of \$2.9 million (US DoEnergy, 2007) and has the backing of the municipal utilities group. A site has been identified and it is envisaged that it will open in 2011. A wind farm of 75-150MW is planned with the 200MW CAES plant as part of the project, with excess wind generation and further off peak electricity used to pump air into underground storage.
- In the US a number of significant schemes are presently being investigated and funded especially in the Mid-West. A large 2700 MW plant in Norton, Ohio has been planned for some 5 years, but construction however has yet to start, since this project has been hampered by a number of planning delays.
- A similar style of project linked with a wind farm is being investigated by Shell Wind Energy Inc and Luminant in Texas. Worldwide several projects of a smaller nature are being demonstrated with examples in Italy, Israel, the former Soviet Union and Japan (Baxter (2006)).

2.3 Mechanical Systems

2.3.1 Flywheels

Technical Summary: Flywheels represent a mechanical form of energy storage in which the kinetic energy of a fast-spinning cylinder contains considerable stored energy. Recent technological advances have modernised the traditional flywheel, improving its efficiency dramatically. Modern flywheel systems are typically comprised of a massive rotating cylinder, supported on a stator by magnetically levitated bearings that eliminate wear and extend system life compared with conventional bearings. To increase efficiency, the flywheel is operated in a low pressure environment to reduce friction with the air. A flywheel energy storage system draws electricity from a primary source to spin the high density cylinder at speeds greater than 20,000 rpm.



When the primary source loses power, the motor acts as a generator and as the flywheel continues to rotate, this generator supplies power to the grid.

Energy Density & Discharge Time: Flywheels have a quoted energy density of 50 – 100 Wh/kg. (Ruddell, 2003; ESA, 2007). The technology described in Case Study 3 has a discharge time of up to 30 minutes.

Energy Efficiency: Flywheels have an efficiency of around 90%, dependent on the speed range of the flywheel (Ruddell, 2003; ESA, 2007).

Development/Deployment status: Although conventional flywheel technology is well established, the new type of technology shown in the Case Study below is only in the demonstration phase.

Figure 6: Beacon Power's Smart Energy 25 kW flywheel

(Source: <http://www.beaconpower.com/products/EnergyStorageSystems/index.htm#>)

Economics: Based on 2005 figures, Case Study 3 is quoted as having a cost per MW of ca. €1050k for which the return on investment = 23%.

Environmental Impacts and Regulatory Issues: With no chemical management and disposal issues to consider, flywheels have some environmental advantages over the battery systems described earlier. Design life for these devices may be only a few years or less, which is an area for future research activity. Subject to stringent safety safeguards applied to the operation of heavy, rapidly rotating objects, a flywheel system should not cause problems to the local area.

Case Study 3: Flywheel Energy Storage System - Beacon Power Corp

Location: DUIT test facility of Pacific Gas and Electric Co, California.

Technology: Flywheels have commonly been used as rotary UPS where the flywheel is coupled to the motor/generator as a power quality aspect to provide back up in the order of a few seconds to minutes. Beacon Power Corp has developed a 100 kW module which differs from the traditional system by focusing upon operating higher rotational speeds rather than mass to increase the energy stored. A patented, co-mingled rim technology (PCRT) has been developed to prevent cracks developing due to centrifugal forces, leading to safety improvements. Other developments incorporated that differ from traditional systems are an evacuated chamber to house the rotors and magnetic lift to support the rotors, both of which minimise friction loss and wear in the bearings. Flywheels can consequently undergo 10s of thousands of cycles and Beacon Power quote a lifetime of 20 years for its flywheels. On 30th September 2007, Beacon Power announced that it will be applying for permission to build its first 20MW frequency regulation plant in New York state.

Purpose: Frequency regulation for distribution grids. The technology has the ability to discharge over periods up to 30 minutes meaning it will be highly suited to variations in wind capacity, allowing increased levels of distributed generation to be deployed. Flywheels can be charged or spun-up when power output of, for example, wind turbines rises above demand and subsequently discharged when the power output falls below that level. Beacon Power Corp envisages arrays of the 100kW modules in systems of around 20 MW capacity. This has been termed the 'Smart Energy Matrix' 20 MW frequency regulation plant. This plant of 200 flywheels can provide 20 MW of up and down regulation equal to 40 MW of swing.

2.4 Electro-Magnetic Systems

2.4.1 Superconducting Magnet Energy Storage (SMES)



Technical summary: SMES is a technology that can store electrical energy in a magnetic field within a cooled super-conducting coil. The coil is cryogenically cooled beyond its super-conducting temperature (-269°C). At this temperature, resistance of the material to electric currents disappears, and the limited electrical resistance allows extremely high efficiencies of up to 97% to be achieved as well as enabling storage more or less indefinitely.

An additional advantage is the immediate release of power which renders the system useful to customers requiring extremely high quality power output.

Energy Density & Discharge Time: Extremely rapid discharge times (ca. 1 second) have been quoted for this technology (Baxter (2006)).

Figure 7: 2 MJ SMES developed by ACCEL (Source: ACCEL)

Energy Efficiency: Efficiencies of up to 97% can be achieved.

Development/Deployment status: This technology appears at present to be under-utilised in power quality applications. There are several 1 MW units worldwide with applications in microchip fabrication facilities an example.

At present the maximum system size available is 10 MW although research is investigating the large scale potential of the technology which is estimated as being 2000 MW (Imperial College, 2003). This technology is undergoing further research and development.

Economics: SMES is still undergoing development and research and as such there is very limited information available on costs, although (Baxter (2006)) quotes a figure of ca. €350 / kW for a specific system type.

Environmental Impacts & Regulatory issues: Extremely low temperatures are required for the superconducting system which represents a safety issue. Larger scale SMES systems could require significant protection to deal with magnetic radiation issues in the immediate vicinity of the plant.

Case Study 4: 2 MJ Superconducting Magnetic Energy Storage (SMES)

Location: Dortmunder Elektrizitäts und Wasserwerke. Germany

Technology: This 2 MJ system being developed by ACCEL is designed to supply 200 kW for a carry over time of 8 seconds. The purpose of the system is ensure power quality through an uninterruptible power supply (UPS).

Sources: Imperial College (2003) http://www.doc.ic.ac.uk/~matti/ise2grp/energystorage_report/node8.html;
ACCEL http://www.accel-instruments.com/pages/2_mj_superconducting_magnetic_energy_storage_smes.html

2.5 Transport Systems

Storage technology can be used within the two types of electric vehicle currently available, Battery Electric Vehicles and Hybrid Battery Electric Vehicles.

Battery Electric Vehicles (BEVs) are powered either by a large electric motor connected to a transmission, or smaller electric motors housed in the wheel hubs. The energy used to power these motors comes exclusively from battery packs housed within the vehicle that must be charged from an external source of electricity. Battery technologies currently used for BEVs include NiMH (see Section 2.1.2), used in the Toyota RAV4-EV plug-in BEV, and Li-ion (see Section 2.1.3), used in the Tesla Roadster BEV.

Hybrid Battery Electric (HEV) technology typically combines an internal combustion engine (ICE) with an electric motor in a number of different configurations, as described in Section 1.3.2.

Battery technologies currently used for HEVs include NiMH (see Section 2.1.2), used in the Toyota Prius HEV and Li-ion (see Section 2.1.3), used in the Toyota Prius conversions to a plug-in hybrid.

Supercapacitors (see also Section 2.1.1) are an alternative technology being developed for use in BEVs and HEVs. Supercapacitors can store and release energy much more quickly and efficiently than battery technologies. Therefore, supercapacitors are being considered for more efficient regenerative braking systems and increased power delivery for acceleration.

Application: Sacramento Regional Transit District in the US is developing a static energy storage system employing parallel supercapacitor banks installed on its trains. The 1MW static energy storage unit will store energy from braking vehicles and use the energy later to accelerate the trains. The storage unit will be charged from regenerative braking and from the DC traction grid. The static energy storage substation is projected to cost 50% less than a conventional DC substation and should reduce operating costs. The project is due to be commissioned in summer 2008.

2.6 Hydrogen for Energy Storage

The use of hydrogen as an energy carrier is a very large issue and could easily form the basis of a specific report. This section is an overview of the issues surrounding hydrogen as an energy storage medium but it is not intended to be an exhaustive discussion of the subject. Although estimates vary, a large-scale hydrogen economy is only expected from around 2030 (EERE, 2002).

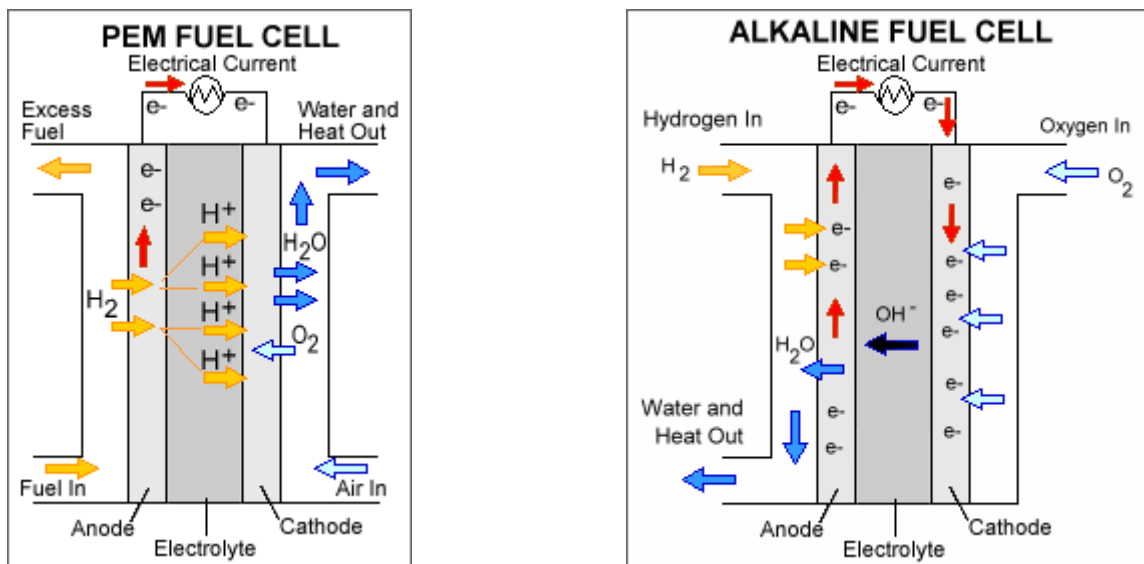
2.6.1 Hydrogen for Electricity Transmission and Distribution

Hydrogen-based energy storage systems are receiving considerable attention at present due to the long timescale over which hydrogen can be stored and because of the potential hydrogen holds for replacing petroleum products as the energy carrier for the transport sector. When coupled with a renewable energy source or low carbon energy technology, hydrogen energy storage has the potential to reduce greenhouse gas emissions.

The essential elements of a hydrogen storage system comprise an electrolyser unit, to convert electrical input to hydrogen during off-peak periods, the storage component and an energy conversion component to convert the stored chemical energy into electrical energy when demand is high or for use in transportation systems.

The electrolyser and fuel cell components can be dedicated or "reversible", capable of electrochemically producing hydrogen or operating in fuel cell mode and converting the hydrogen back to electricity. Proton Exchange Membrane (PEM) fuel cell technology (Figure 8) has been most extensively explored for reversible electrolyser operation, but solid oxide fuel cell (SOFC) and alkaline fuel cell (AFC) technologies can also be applied reversibly. One of the principal concerns of hydrogen systems is the whole cycle efficiency. Energy loss is inherent in the system when electricity is converted to hydrogen, stored, transported and then re-converted to electricity in a fuel cell. Estimates of this energy loss range from 60% to 75%. (Gordes, J. N. et al, 2000). Phosphoric Acid Fuel Cells (PAFCs) are considered one of the most mature fuel cell technologies typically used for stationary power generation. They are more tolerant of impurities within the influx gases than PEM cells, which are easily poisoned by carbon monoxide (CO). PAFCs are 85% efficient when used for the co-generation of electricity and heat but less efficient (37 – 42%) at generating electricity alone (EERE, HFCIT, 2007). A typical PAFC costs between \$4,000 and \$4,500 /kW to operate.

Figure 8: Diagrammatic representation of a Proton Exchange Membrane (PEM) and an Alkaline (AFC) hydrogen fuel cell



Source: http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

More advanced fuel cell technologies are under development and include: Direct Methanol Fuel Cells (DMFC); Molten Carbonate Fuel Cells (MCFC); Solid Oxide Fuel Cells (SOFC). MCFCs and SOFCs operate at extremely high temperatures of around 620°C and 1,000 °C respectively. MCFCs are approaching 60% efficiency for the conversion of fuel to electricity and it is anticipated that SOFCs will achieve similar levels of efficiency. When the waste heat is captured and used efficiencies can be as high as 85% for both technologies.

Hydrogen has a low volumetric energy density 12.7 MJ/m³, around 25% that of methane (Bossel U. et al., 2003), therefore it is stored and transported as a compressed gas or in liquefied state. Hydrogen's boiling point is around -273°C at 1 atm pressure, so making liquefaction very energy intensive. Alternative hydrogen storage technologies under development include compressed underground storage in aquifers or salt caverns, chemisorption to metal hydrides and fullerenes, and physisorption to active carbons or carbon nanotubes (INVESTIRE, 2003).

Wind Hydrogen Limited plans to develop a scheme in Hunterston, Scotland, to demonstrate that it is possible to provide a renewable energy and hydrogen-fuelled supply for Scotland. The system aims to mitigate against the inherent intermittency of wind power and create a renewable energy system that responds to consumer demand. It is intended that the initial demonstration facility will accommodate a 5 MW plant, with the potential for a future expansion to 50 MW. The plant aims to allow hydrogen fuelled electricity production over a maximum of four hours per day. This in turn requires production and storage of hydrogen over a minimum of 10 hours per day according to Wind Hydrogen Ltd (2007). The engineering contractor, AMEC Ltd. has already completed design engineering studies and costing for the pilot plant.

2.6.2 Hydrogen for Transport and Mobility

Even when compressed hydrogen is stored in pressurised tanks, carrying enough hydrogen onboard to travel the same distance as gasoline-powered vehicles before refuelling is a significant problem for Fuel Cell Vehicles (FCVs). Higher-density liquid fuels such as methanol, ethanol, natural gas, liquefied petroleum gas and gasoline can be used for fuel, but require vehicles to use an onboard reformer to convert the fuel to hydrogen. This increases costs, energy and maintenance requirements of the FCV.

In addition some CO₂ is released by the reforming process, although less than from typical present day gasoline-powered engines. Direct Methanol Fuel Cells (DMFC), Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC) are being developed, all of which can be powered directly using an organic fuel, therefore dispensing with the need for an external reformer. However, the extremely high temperatures at which MCFCs and SOFCs operate reduces the suitability of these technologies for transport applications. DMFCs offer good potential for use in the transport sector, but their development is estimated to be 3-4 years behind that of other fuel cells, such as PEM cells, powered by pure hydrogen.

Case Study 5: CLEAN URBAN TRANSPORT FOR EUROPE (CUTE) - A Hydrogen Fuel Cell Bus Project in Europe 2001 – 2006

The European Commission, in conjunction with partners, set out to develop and demonstrate an emission-free and low-noise transport system, based upon hydrogen fuel cell technology. Over the period 2003 – 2005, twenty seven hydrogen fuel cell buses were placed in the transport fleets of nine European cities in seven different countries. At the same time, infrastructure such as hydrogen production, refuelling and maintenance systems were also installed. The buses were placed on normal public transport routes and data collected against a range of performance measures.

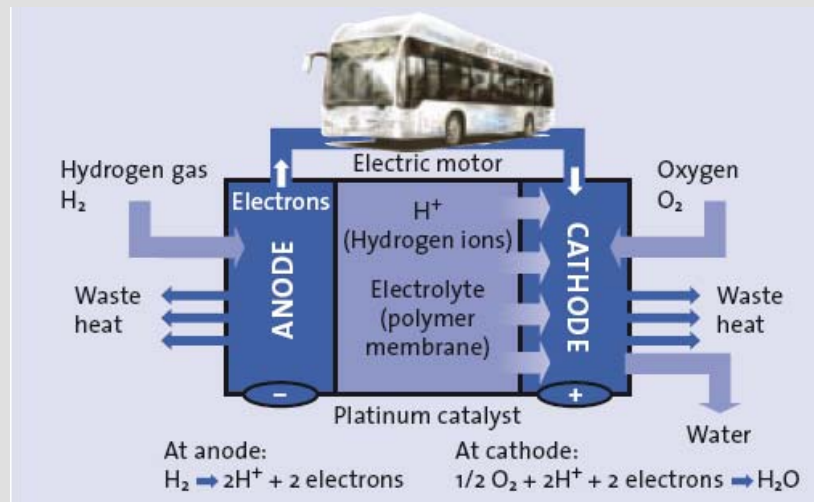
The project explored a wide range of pathways to produce hydrogen as a transport fuel for fuel cell vehicles, including steam reformation, water electrolysis and centrally produced hydrogen as a by-product of other processes.

Motive power for the buses used in the CUTE project was provided by Proton Exchange Membrane (PEM) fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some fuel cells.

The buses used for the study were based upon the 12 m series of EvoBus with a fuel cell drive train developed on the conventional Mercedes Benz Citaro. The bus was named The Fuel Cell Citaro. The fuel cell drive train is the HY-205 P5-1, the fifth generation of heavy duty drive trains developed in Ballard, Vancouver.

The fuel cell buses are equipped with nine tanks, which together hold 44 kg of gaseous, compressed hydrogen. These tanks feed two fuel cell modules which provide more than 250kW of electrical power, and acceleration performance levels that are comparable to standard diesel engines. The average fuel consumption of the CUTE bus fleet varied between 20.4 and 31.5 kg/100km across the nine European cities which hosted buses, with Hamburg having the lowest consumption and Porto the highest.

Figure 9: Schematic of a Proton Exchange Membrane hydrogen fuel cell

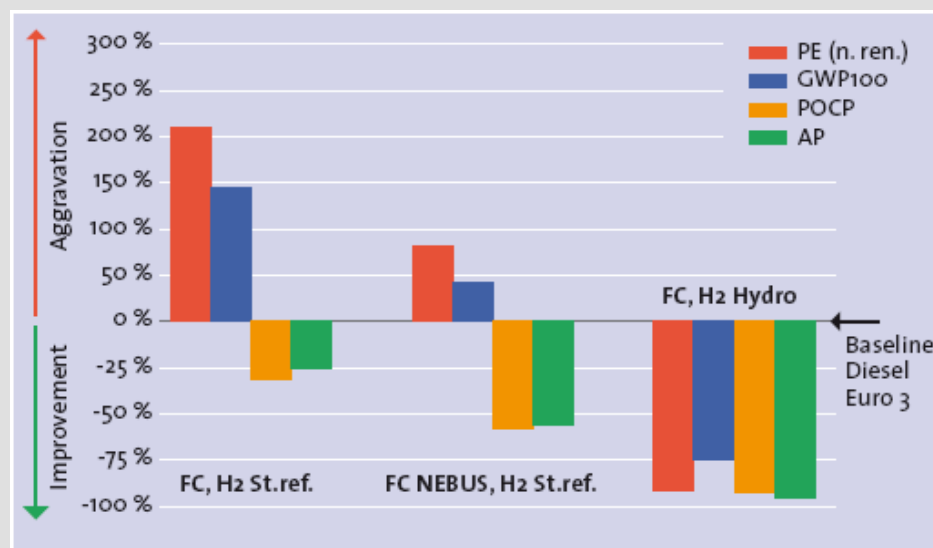


Source: www.sustainability.dpc.wa.gov.au

On the infrastructure side, the CUTE project tested a number of technologies related to hydrogen production and purification, in addition to compression, storage and refuelling systems. Hydrogen was externally sourced in London, Luxembourg, Madrid (partly) and Porto. The other cities produced hydrogen on-site using either water electrolysis or steam reforming.

The main results of a Life Cycle Analysis (LCA) for the Fuel Cell bus system, including production, infrastructure and bus operation, are shown in Figure 10. Results are compared with analogous analyses for diesel bus systems. FC refers to the Fuel Cell Citaro, FC Nebus refers to the predecessor prototype of the Citaro.

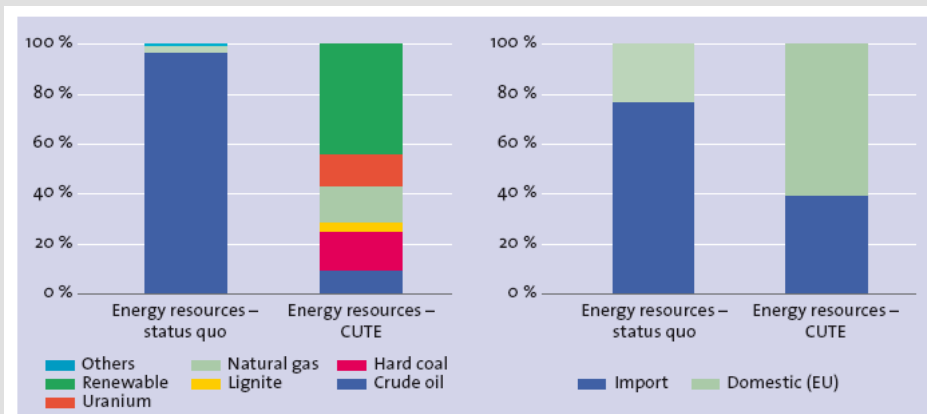
Figure 10: Comparison of Life Cycle Analysis results for fuel cell buses with a diesel bus system.



PE is Primary Energy demand from non-renewable sources. **GWP100** is the Global Warming Potential. **POCP** is the summer smog formation potential. **AP** is the Acidification Potential.

The hydrogen fuel cell bus systems contribute to an improvement in air quality over diesel bus systems. The environmental profile of the hydrogen fuel cell bus system is dependent on the hydrogen production method, either steam reforming or hydrolysis, and the regional conditions for supply of natural gas and electricity. However, the use of hydrogen fuel cell systems enables a greater use of renewable resources specifically and in general diversifies the energy sources used within the system. Additionally, the import dependency for the CUTE fleet was reduced by almost 40%.

Figure 11: Comparison of energy share and sourcing for public transportation and in CUTE.



Source: <http://www.fuel-cell-bus-club.com/index.php?module=pagesetter&func=viewpub&tid=1&pid=2>

2.7 Summary

Table 1 summarises the storage technologies discussed above. It shows the technology types, their technical characteristics, relative development and deployment status, illustrative economic costs and suitability for different applications.

Table 1: Inventory of current energy storage technologies⁷

(Various Sources, including: US Department of Energy (EERE 2006); The INVESTIRE network (INVESTIRE, 2003); Energy Storage Association (ESA, 2007); UK Department of Trade and Industry (DTi, 2004; DTi, 2006); Baxter (2006))

Technology Type	System Energy Density	Efficiency of Recovery	Development	Deployment	Illustrative Economic Costs	Current Investment		Advantages	Disadvantages	Suitability for		
						EU	Rest of World			Energy Management	Power Quality	Transport
Advanced Battery Systems												
Super-capacitors	0.1 - 5 Wh/kg	85 - 98%	Developing	Widespread (small scale)	2002: 200-1000 (€/kW)	3.6M€ under Joule III FP4	Un-known	Long life cycle, high efficiency	Low energy density Toxic and corrosive compounds	✓✓	✓✓✓	✓✓✓
Nickel Batteries	20 - 120 Wh/kg	60 - 91%	Available	Limited	200 - 750 (€/kWh)			High power and energy densities Good efficiency	NiCd: Cadmium highly toxic NiZn, NiMH and Na-NiCl ₂ require recycling	✓✓	✓✓✓	✓✓✓
Lithium Batteries	80 - 150 Wh/kg	90 - 100%	Available	Growing for small scale applications	150 - 250 (€/kWh) [High energy, industrial application]	5M€under FP6	US, Japan, Taiwan	High power and energy densities High efficiency	High cost Lithium oxides & salt require recycling Polymer solvents and carbon must be made inert	✓	✓✓✓	✓✓✓
Lead-Acid Batteries	25 - 45 Wh/kg	60 - 95%	Available	Widespread	50 - 150 (€/kWh)			Low capital cost	Lead requires recycling	✓✓	✓✓✓	✓✓✓
Zinc-Bromine Flow Batteries	37 Wh/kg	75%	Early phase of commercialisation	Limited	2MWh battery (1.8m €)			High capacity	Low energy density	✓✓✓	✓✓	
Vanadium Flow Batteries		85%	Early phase of commercialisation.	Limited	1280€/ kW			High capacity	Low energy density	✓✓✓	✓✓	

⁷ Values are representative of stationary and transport applications.

Tech- nology Type	System Energy Density	Efficiency of Recovery	Development	Deployment	Illustrative Economic Costs	Current Investment		Advantages	Disadvantages	Suitability for		
						EU	Rest of World			Energy Manage- ment	Power Quality	Trans- port
Metal-Air Batteries	110 - 420 Wh/kg	~ 50%	Electrically rechargeable cells - developing	Limited (large scale)				High energy density Low cost. Environmenta lly benign	Poor electrical rechargeability Short recharge lifetime	✓✓✓	✓	✓
Sodium- Sulphur Batteries	150 - 240 Wh/kg	> 86%	Available	Mainly in Japan	170€/kWh		Japan	High power and energy densities High efficiency	High production costs. Na requires recycling	✓✓✓	✓✓	✓
Fluid Storage												
Pumped Hydro- Electric	N/A	75-85%	Available	Widespread - 90GW worldwide	140m - >680m €for a 1000MW plant	Limited	Limited	High capacity, relatively low cost per unit capacity	Disturbs local wildlife and water levels	✓✓✓	✓✓	✗
Com- pressed Air Energy Systems	N/A	80% (Alabama plant)	Available	Limited, one site in the USA and one in Germany	400€/kWh at plant in Alabama	Limited testing (Italy)	Planned 2.7GW plant (Norton Ohio)	High capacity, relatively low cost per unit capacity	Problematic in obtaining sites for use: Norton Ohio site is experiencing several legal proceedings	✓✓✓	✓✓	✗
Mechanical Systems												
Flywheels	30-100 Wh/kg	90%	Available		3000-10000 (€/kW)			High power	Low energy density	✓✓	✓✓✓	✓
Electro-Magnetic Systems												
Super- Conductin g Magnets		97-98%	Developed up to 10MW, potential to increase this to 2000MW	In power quality applications, potential for diurnal storage	350€/kW		Japan, USA	High power	Health impacts for large scale sites	✓	✓✓✓	✗
Hydrogen												

Technology Type	System Energy Density	Efficiency of Recovery	Development	Deployment	Illustrative Economic Costs	Current Investment		Advantages	Disadvantages	Suitability for		
						EU	Rest of World			Energy Management	Power Quality	Transport
H ₂ Fuel Cell	N/A (System outputs <1kW - 3MW)	25 - 58%	Research/developing/ marketed	Limited	6,000 - 30,000 €/kWh	Hydrogen & fuel cell technology platform	Freedom CAR (USA)	Hydrogen can be stored long term Range of cell types for different applications	Expensive catalysts or processing often required	✓✓✓	✓✓✓	✓✓✓
H ₂ Internal Combustion Engine (ICE)	N/A	N/A	Developing	Limited		BMW	Ford / California			✓	✓	✓✓✓

Key to Table 1	
✓✓✓	Suitable
✓✓	Partially suitable
✓	Limited suitability
✗	Unsuited

3. RESEARCH AND DEVELOPMENT PROGRAMMES

The inventory of energy storage technologies highlights a number of technologies where Japan and USA are world leaders. It is important to consider ongoing work in Europe as technologies focussed upon the European market are likely to be more compatible with the European energy networks and demand. Of particular interest is the progress being made under the European Framework Programmes.

3.1 European Research

The Sixth Framework Programme (FP6) is currently ongoing and therefore provides a good synopsis of present European Commission funded research as many projects are due to be completed during 2008. The list of European Electricity Projects (European Commission 2007b) provides a summary of 60 projects funded under FP6 and 13 under the Intelligent Energy Europe Programme. Of these projects three are directly researching technologies that promote energy storage. This research is directed mainly towards the development of distributed energy resources and the integration of renewables into the grid. Three important ongoing programmes on energy storage are:

- **ALISTORE:** This project is aiming to develop advanced lithium batteries as a storage system. The applications envisaged are energy storage systems, hybrid electric vehicles and grid enhancement architectures. ALISTORE is based upon the use of nano-powders and nano-composite electrodes/electrolytes. It is hoped that this approach will revolutionise the structure and production of battery cells.
- **Night Wind:** Project based in the Netherlands. Essentially a form of cold energy storage, large refrigerators would be cooled during the night. The project is aimed for food refrigeration, through night time cooling there would be the potential to store 50,000 MWh of energy. Refrigerators would then be allowed to warm by 1 °C during the day by switching them off. The concept is building upon the current practice of refrigerators being switched off for a few minutes during peak demand, this project looks at extending that to hours instead of minutes. The technology required is the generation of software to match refrigeration temperature and electricity demand. It is currently unclear how much energy this scheme could offset but the European electricity demand of cold storage is considerable when compared to wind capacity.
- **Demo-restore:** This project focuses on the short to medium storage of energy. A focus has been placed upon PV systems with the storage of daytime production via lead-acid batteries. The geographical focus of the project is towards arid and island regions which do not have access to electricity networks and therefore operate as stand alone systems. Solar home systems are an example of such and the battery is currently the weakest point of these systems. Testing is ongoing towards developing improvements in lead-acid batteries.

Under FP6 a number of research projects were also undertaken considering energy storage technologies for the transport sector, these include:

- **HyHeels:** This project aimed to provide a supercapacitor-based energy storage system for optimising hydrogen-powered and hybrid-electric vehicle systems. The main work focuses included: increasing the opening voltage of ultra-capacitors; reducing the cost of producing electrodes; reducing the cost of cell production; development of a supercapacitor controller device.

The HyHeels project was seen as a necessary prerequisite for the development of a hybrid vehicle able to achieve ‘well to wheel’ energy efficiency exceeding 35% on the extended European urban driving cycle, or near zero CO₂ emission and pollutant emissions when fuelled by hydrogen produced from renewable sources.

- The **ILHYPOS** project again aims to develop supercapacitor technology for both transport and stationary applications such as combined heat and power systems. However, the focus is different to HyHeels with the aim here to develop supercapacitors based on the use of ionic liquids as electrolytes and on a novel hybrid configuration using electronic conducting polymers (ECPs) as positive electrodes. The completion of ILHYPOS is thought to favour the positioning of Europe as a leader in the supercapacitor field and enhance the environmental benefits of this technology.
- **POMEROL:** The technology to be addressed in this project is Li-ion batteries for hybrid electric vehicles. The objective of the project is to develop new materials that will greatly reduce the cost of high power Li-ion batteries to €25/kW.

FP6 has also contributed some €300 million to research, development and demonstration projects in the field of hydrogen and fuel cell technologies. The research areas pursued include: H₂ production and distribution; H₂ storage; high and low temperature fuel cell research; transport applications; stationary and portable applications (EC, 2006). Through FP6 the European Commission has also supported the creation of the European Hydrogen and Fuel Cell Technology Platform (HFP), an industry-led body that brings together all those with a stake in the development of hydrogen and fuel cells technologies. The projects directly funded under FP6 and the strategic research agenda drawn up by the HFP give inputs to the research and development projects that will be funded under the Seventh Framework Programme for Research (FP7).

FP7 is currently being tendered and this has some focus towards energy storage technologies in the research area. ‘Topic ENERGY.2008.10.12: Novel material for energy applications’ is one such example and aims to focus upon novel materials. The FP7 sustainable surface transport programme includes a call for vehicle/vessel and infrastructure technologies for optimal use of energy, which aims to develop vehicle and infrastructure technologies to reduce energy consumption, particularly smart components and auxiliary systems to reduce energy consumption and/or make use of energy harvesting.

3.2 International Energy Agency

The International Energy Agency (IEA) has an “Efficient Energy End-Use Technologies” research and development programme that contains 14 implementing agreements, of which one, agreed in 1978, is on energy storage. The name of the implementing agreement is “Energy Conservation through Energy Storage” (ECES) with active participants including Belgium, Canada, Denmark, Finland, Germany, Japan, Norway, Sweden, UK, USA and Turkey.

The main focus of current research workstreams under the ECES agreement is thermal energy storage with 4 ongoing workstreams:

- Transportation of thermal energy utilising thermal energy storage technology;
- Optimised industrial process heat and power generation with thermal energy storage;
- Sustainable cooling with thermal energy storage;
- Thermal response test for underground thermal energy storage.

Thermal energy storage aims to store heat energy, primarily either through underground thermal energy storage (UTES), which uses soils, bedrock or groundwater, or using materials that show a phase change (e.g. water/ice) that results in the uptake or release of large amounts of energy.

The ECES 2006-2010 strategy plan proposed a workstream focussed on electrical energy storage and distributed generation (IEA, 2006). However, the current planned workstreams are listed as: Applying energy storage in ultra-low energy buildings; and, thermal energy storage applications in closed greenhouses.

Recent discussions with the Operating Agent for the IEA Implementing Agreement on Electricity Networks Analysis, Research and Development (ENARD) have confirmed that the ECES agreement will focus on heat storage work and that ENARD will take the lead in work related to electricity network storage issues. The next meeting of this group is in May 2008 and we understand there are a number of potential workstreams where electricity energy storage is involved.

3.3 Conclusion

Current R&D in the area of energy storage does not appear to reflect the potentially key role that electricity network energy storage may be able to play in enabling a cost effective low or zero carbon electricity system with full utilisation of intermittent renewable energy electricity generation.

The focus in the recent past appears to have been on heat storage and in the area of transport batteries and fuel cells. The latter area is now becoming closer to market and may best be driven by legislation, mobilising the resources and financial strength of the automotive industry.

Given the combined commercial, regulatory and technical barriers to the development of electrical network energy storage identified in this report and elsewhere we would endorse the heightened priority given to this area of research in the Commission Communication referred to in the introduction to this report (Section 1.1, COM(2007) 723 final) and recommend a number of actions related to this area in our conclusions and recommendations at the end of the report.

4. PROMISING EMERGING TECHNOLOGIES

4.1 Introduction

The following sections briefly discuss the technologies that appear to have the most potential for European deployment. The technologies are discussed in the context of their principal application(s), and in the light of the numerous differences that exist between power quality, energy management and transport end uses. The criteria used to select the most promising technologies were:

- *Scope for development.* Our analysis has tried to focus on those technologies that have a proven capacity to develop and be further improved.
- *Demonstrable fitness for purpose.* Building from the previous criteria, the most promising technologies must also have been demonstrated with the application considered. Successful demonstration of a technology includes good cost and efficiency credentials.

The technologies are grouped by their primary role. Some of the energy management technologies, for example redox batteries, are also capable of meeting a number of power quality requirements and so have additional flexibility and wider potential revenue streams.

The technologies put forward in this Section are based upon our review of the current literature and our contacts with the industry. This brief review exercise provides an indication of priority technologies but cannot be considered comprehensive.

4.1.1 Power Quality

Flywheels: This is a mature technology that has been significantly modernised in the US by Beacon Power Corp. Whilst presently in the demonstration phase, there exists good potential and plans for power quality improvements in conjunction with wind and solar energy. The latest 100 kW unit has the potential to contribute measurably to power quality regulation. Flywheels have limited environmental impact and would help to improve the power quality of intermittent renewables therefore also improving their economic value.

Sodium-Sulphur Batteries (NaS): The US DoE has demonstrated the peak shaving potential of NaS devices. They appear to be useful devices for improving performance in many electricity networks (UK DTI 2006).

Superconducting Magnet Energy Storage (SMES): This technology, which is suitable for power quality applications, appears to have no major barriers to wider deployment. Energy management deployment would require significant scale up and is still some way off demonstration and as such has not been considered in Section 4.1.2 below.

Overall: The power quality field has to date seen very limited deployment as a form of large scale power regulation, such as integration with renewable energy sources. This is the greatest potential growth area. The demand for power quality from commercial customers is important but will be much more self-determined and dependent upon the quality of future energy supplies. It is likely that further research and demonstration will be required before the above technologies can be widely deployed as a form of improving network power quality.

4.1.2 Energy Management

Flow Batteries: Flow batteries, particularly vanadium redox, appear to have great potential for wider deployment in conjunction with wind farms or more widely in electricity networks (depending on regulatory structures and market incentives – see later Section within this report). There are a number of examples installed or under construction and the installation at Sorne Hill, Ireland will provide an important perspective of how this technology fares within a liberalised energy market: it will allow an assessment of whether it can demonstrate increased value for intermittent renewables by making the energy dispatchable. In Hokkaido, Japan, Sumitomo has installed a 4MW vanadium flow battery at the Tomamae Wind Farm which has been successfully operational since January 2005 (Baxter, 2007). Development and deployment have taken place in Canada, Japan and Australia. The limited environmental impacts and potential to increase the penetration and value of intermittent renewables are important reasons to monitor the progress of existing projects and disseminate this information.

Compressed Air Energy Systems (CAES): This technology is mature but has been included here because of its recent application in combination with wind farms. CAES is receiving strong support in the US at present with one notable scheme under construction. CAES deployment in Europe will however be restricted by the space availability of storage caverns for the compressed air. In the US planning disputes have delayed one large-scale project in Ohio significantly (since 2001). The technology is well suited to make use of off-peak power and therefore could be successfully integrated into networks with high wind penetration. A major advantage of this technology is the large amounts of energy that can be stored, for example the planned Ohio scheme is 2700 MW. A wider issue with CAES is that many suitable caverns are currently used for gas storage and are likely to be required into the future given the increasing importance of security of supply issues with gas.

Sodium-Sulphur batteries (NaS): Sodium-Sulphur batteries have achieved commercial status in Japan with over 50 operational examples. Whilst the technology has been available for several years, recent improvements in efficiency mean that it now has one of the best energy densities of all technologies. The 34 MW installation in Japan is an example of this and will be the largest combined wind and storage installation in the world (Baxter, 2007). A major drawback environmentally is that NaS batteries have a limited number of charge/discharge cycles and hence a finite lifetime dependent on the number and depth of charge and discharge cycles and how frequently they occur or are required.

Hydrogen generation and storage has been the subject of many studies for energy management, however no large-scale demonstration of the technology for this application has taken place. The main focus for energy management applications has been to increase the utilisation of renewables, in particular wind energy. Water electrolysis technology, which is used to convert electrical energy to hydrogen, is a mature technology. The main limitation at the present time that is common to all hydrogen applications is hydrogen's low energy density and the difficulties in storing large quantities in a manageable volume. There are significant research programmes underway in this area and in improving the efficiency of the electrolysis and fuel cell energy conversion cycles. Overall hydrogen is a promising technology for the mid to longer term but a number of the technologies referred to above are likely to be exploited prior to the significant developments in hydrogen technology and storage that will be required for it to become a cost effective option for energy storage on a large scale.

Overall: A general observation on energy management technologies is that relatively little research and development appears to be taking place in the EU, although all are primarily being marketed for use in conjunction with wind power. It is interesting to note that storage is being promoted in combination with wind power when a number of studies have shown it can provide wider benefits by being integrated in a distribution network – this may well be because the commercial and regulatory barriers to wider exploitation are significant, while the benefit of firming-up intermittent renewables and making them dispatchable is clear. Japan is leading the field in flow batteries and NaS and has considerable operational experience in terms of their actual efficiency, costs and downtime. CAES has potential to eventually utilise the extensive European gas network but will be limited by appropriate locations. Flow batteries are the newest of the technologies, whereas both NaS and CAES technologies have existed for a number of years but have not been widely developed.

As indicated above, increased integration of intermittent renewable energy technologies can be achieved through the installation of flow batteries, CAES and/or NaS. An advantage of flow batteries and NaS is that they can act as both forms of energy management and power quality. CAES would also require some form of power quality to be integrated so that short-term voltage fluctuations do not damage network infrastructure. The above technologies are generally only designed to meet generation shortfalls relative to demand on an hourly to diurnal timescale. Therefore, large-scale utilisation of storage technologies linked to intermittent renewables would require that sufficient alternative generation could be brought online within these timescales should conditions result in longer term gaps in generation from the intermittent renewables. This area is considered further in the next section of this report.

4.1.3 Transport and Mobility

In Section 2, a number of technologies were identified that are currently used within the transport sector to yield system efficiency gains and a cleaner, more secure transportation system. Both hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs) are more efficient than typical conventional gasoline-fuelled vehicles. Both BEVs and HEVs rely on an internal electricity store and there are two emerging technologies that show promise for this role; advanced batteries - notably Lithium-ion technologies - and supercapacitors.

Lithium-ion batteries occupy a strong position in the portable battery market due to their high charge densities and charge/discharge efficiencies. The automotive industry is the main driver behind the development of Li-ion batteries with, for example, the Tesla roadster using a Li-ion battery system. Economically, Li-ion batteries are mainly in competition with Ni-MH batteries, which are the incumbent technology in a number of current BEVs and HEVs. However, Li-ion batteries offer greater charge/discharge efficiencies over Ni-MH and much research effort is focussed on improving the energy density of Li-ion batteries (e.g. FP6 project POMEROL). Current research suggests energy densities of > 200 Wh/kg for advanced Li-ion batteries. One of the objectives for Li-ion batteries, and other advanced battery energy storage systems, must be to improve the system lifetime.

Currently, supercapacitors are often used in conjunction with batteries to reduce the frequency of charge/discharge requirement for the battery system. However, supercapacitors are under development to compete directly with advanced battery technologies as the main energy storage system in BEVs and HEVs. The most advanced supercapacitors can achieve energy densities of greater than 60 Wh/kg. More importantly for transport applications however, supercapacitors have extremely long rated lifetimes, over 300,000 charge/discharge cycles for carbon nanotube enhanced supercapacitors.

In BEVs and HEVs, where energy efficiency gains are achieved by storing energy during braking and subsequently released to aid acceleration, cycle lifetime is paramount. Research and development efforts must focus on improving the energy densities of supercapacitors if they are to provide the principal power source for electric vehicles.

Environmentally, electric vehicles, incorporating advanced battery or supercapacitor technologies, typically achieve greater energy efficiency than current conventional gasoline based vehicles and therefore reduce point of use carbon emissions (see Section 1.5.2).

Hydrogen has been identified for many years as a promising future technology for transport applications, potentially providing almost complete reduction in point of use emissions. There is significant global funding for research into hydrogen as a source of motive power; both the US (e.g. EERE, 2007) and the EU (e.g. HFP, 2007) have dedicated research programs, and the automotive industry is also engaged in developing this technology. Strategically, one of the clearest problems arising from use of hydrogen as a transport fuel is displacing the gasoline-based system that is currently in place and has a huge asset base. However, the environmental credentials of a hydrogen based transport system are being assessed through projects such as the EU's CUTE project (Case Study 5). It is clear from this programme, placing hydrogen fuel cell buses into the fleets of nine European cities, that a hydrogen-based transport system can have significant environmental advantages. The CUTE program demonstrated that environmental benefits are strongly dependent upon the hydrogen production technology. Optimal environmental performance was achieved by the fleets using hydrolysis for hydrogen production, which improved the summer smog potential and acidification potential by around 90% in comparison with a standard Euro 3 diesel bus. In addition the global warming potential of the buses' emissions was reduced by around 75% in this case. The CUTE example also demonstrated a diversification of the primary energy demand, with less dependence on non-renewable sources as well as importing less energy from outside the EU.

Overall: Energy storage technologies for the transport sector are developing rapidly and the initial focus lies in improving the efficiency of the conventional internal combustion engine (ICE). On a slightly further time horizon, the research focus is upon replacing the conventional ICEs with battery electric vehicles or hydrogen ICE or fuel cell vehicles. As established by the CUTE program, the latter proposal incorporates the added challenge, that of developing a full hydrogen infrastructure.

5. POLICY CHALLENGES

Section 4 has identified the most promising energy storage technologies and potential applications. This Section aims to relate these opportunities to the current EU policy challenges, to help identify appropriate recommendations.

5.1.1 Energy Security

Storage technologies have the potential to play an important role in the future of energy security within the EU. As mentioned previously, deploying storage technologies can:

- Provide ‘Black Start Capacity’, this is a power source which is needed to start many conventional forms of power generation in the event of a partial or full grid failure;
- Minimise the risk or magnitude of sudden fluctuations in voltage levels;
- Provide a time interval in which emergency measures can be deployed;
- Increase the stability of localised grids or vital electricity infrastructure.

The shift towards Europe-wide electricity markets may strengthen the case for deploying storage technologies which can be integrated into the European grid, thereby improving the power quality and security of supply.

The key role of energy storage in terms of security of supply is likely to be in enabling the increased penetration of renewables and in particular intermittent renewables, into EU energy markets. If storage can fulfil its potential in enabling very high percentage penetration of renewables into electricity markets it will in turn deliver a high level of energy security. The issue of achieving EU RES targets and the role of storage in enabling a full contribution from intermittent renewables is considered in the next section of this report.

A further energy security consideration in the wide scale exploitation of renewables is the selection of different renewable futures: local renewables exploited in small scale units close to the sites of energy demand will supply a greater degree of energy security but at a relatively high cost.

Larger scale renewables, for example offshore wind arrays, will - in combination with a European Transmission Grid - most likely supply the cheapest renewable energy solution in the medium term but will potentially be more open to large scale disruption by, for example, malicious acts.

The most likely solution will depend on Member States’ renewable energy support policies and therefore be a mixture of large remote renewables generation combined with local, smaller scale applications.

5.1.2 Achieving RES Targets - Intermittent renewable sources and storage

The EU has set itself demanding targets for the growth of renewables generation by 2020 and beyond. The state of commercial and technical development of the various RE sources means that a large proportion of this growth in renewable energy will be from intermittent sources, in particular wind and solar energy.

Intermittent sources of renewable energy, such as solar photovoltaic and wind, can over a year be guaranteed (within reasonable limits) to supply a particular quantity of energy. There will be ‘good’ and ‘bad’ years depending on variations in seasonal weather patterns but within certain bounds a certain level of energy can be relied upon with a high degree of certainty.

Where there is a difference between the intermittent renewable energy sources and the more traditional ones such as gas, coal and nuclear, is in the supply of power as opposed to energy. The intermittent sources of renewables, by their very nature have an output that changes with time on a second by second or minute by minute basis – the wind gusts and the sunlight incident on the ground varies with cloud cover and the angle of the sun. The power an individual intermittent renewable energy source can supply is therefore unpredictable – at least on timescales greater than a few hours.

Alternating Current (A.C.) transmission and distribution systems, which dominate the delivery of electricity in all developed countries, require the balancing of supply and demand on a second by second basis – *the load on the system must, within tight bounds, match the power being generated*. This is generally achieved by having a series of systems in place that predict the load (demand) at a given time and scheduling power generation plant attached to the system to meet this load. Variability is managed by having a number of plant types that are held in reserve, both so called ‘spinning reserve’ - where the plant is turning and ready to generate at very short notice (e.g. to cover for an unpredicted rise in demand at the end of a particularly popular television show) - or ‘warm’ plant that can be brought on stream within a matter of hours to cover for un-forecast events.

Individual intermittent renewable energy generators cannot be relied upon to provide power at a given time. However when a larger number of generators are taken together, especially across geographically spread regions, there is an improved degree of certainty that power can be provided. This is referred to as the ‘capacity benefit’ from the renewable energy technology.

A number of studies (National Grid 2003, Ilex 2002, Grubb 1987) have been carried out in the UK examining the ability of intermittent sources of renewable energy to replace conventional plant. The studies all come to the same conclusion, which is that as the percentage of intermittent renewable energy sources increase there is a decreased ‘capacity benefit’ and therefore an increased requirement for capacity margin to be provided by conventional generation. As an example the Ilex report (Ilex 2002) examined the consequences of adding to the UK electricity system increasing amounts of wind while maintaining the reliability of supply requirements. The results for a high demand scenario with a peak demand of 75,700 MW and a range of wind penetration levels are summarised in the table below:

Table 2 - High Electricity Demand Growth Scenarios Considered for Great Britain with Varying Levels of Wind Penetration by 2020

Peak Demand (MW)	Energy from Wind (%)	Installed Wind Capacity (MW)	Conventional Capacity Required (MW and Margin)	Excess Capacity (MW)	Excess Capacity Margin (%)
75,700	0	0	90,083 = 19%	15,983	21
75,700	10	9,900	86,800 = 15%	22,600	30
75,700	20	24,000	84,000 = 11%	33,900	45
75,700	30	38,000	82,500 = 9%	46,400	61

N.B. All scenarios above also include 1,600 MW of other renewable capacity.

Overall the conclusion is that capacity margins increase dramatically as higher percentages of wind are added to the overall network generation mix. So while wind-generated electrical energy replaces energy from other generators it does not remove the need for other generating capacity.

Furthermore, in the UK studies at least, the conventional plant capacity does not fall below the peak demand and it is suggested (Laughton, 2007) that this can never be the case i.e. conventional plant capacity will always be required to exceed peak demand to maintain system reliability.

The capacity benefit does however increase as larger geographical areas are considered. For example, there is a reasonably high likelihood of a still day over a County in the UK or a Lander in Germany but the chances that there is no wind across the whole UK or Germany is less likely and it is even less likely to be still across the whole of Western Europe simultaneously. Therefore as long as suitable transmission capacity is in place, the full benefit of a weather front moving across Europe can be exploited.

The capacity factor issue has important implications for storage. Storage can in principle convert some of the output from an intermittent renewable energy source to firm supply. This can reduce the amount of conventional plant that is held in reserve to meet the system reliability requirements and - in addition - can possibly provide a greater degree of flexibility, supplying services to the network market participants that the plant it replaces may not be capable of supplying.

It should not be assumed however that this creates an essential role for storage. As Milborrow (2007) states:

‘When it comes to sourcing the most economic method of providing reserve, system operators choose the least cost options, provided that they meet their technical requirements. Storage has no intrinsic merits for coupling with wind energy, as an early analysis by Farmer et al made clear: ‘there is no operational necessity in associating storage plant with wind power generation up to a wind output capacity of at least 20% of system peak demand.’

This quote deals implicitly with the idea that storage might help to ‘level the output’ from intermittent renewables. This is possible; but it simply adds to wind energy’s costs – unless the added value exceeds the extra cost. In this context, the demonstration project referred to in this report at Sorne Hill wind farm in Ireland (Case Study 1, Section 2.1.5) will be an interesting test of the balance between the costs of storage and the value it can add to an intermittent renewable such as wind.

Storage may or may not be the most effective way of providing additional spinning reserve (or instantaneous back-up) for the system – this, again, depends upon its costs.

The breakeven costs for storage are controlled by, *inter alia*:

- The value of electricity through the day and in particular the difference between the highest and lowest value (the ‘spread’)
- The lifetime of the storage device
- The rate of return demanded by the developer

The breakeven cost is in the range 700-1,400 €/kW (Strbac and Black 2004), the higher range depending on the device being able to sell the wider services described earlier in this section.

In the absence of storage, the reserve capacity is most likely to be supplied by open circuit gas turbines (OCGT). The advantages that storage has over the OCGT approach are (i) savings in fuel costs, (ii) reduction in carbon dioxide emissions and (iii) an increase in the amount of wind energy that can be accommodated on the networks. Strbac and Black (2004) also calculated that the value of storage over and above OCGT was of the order of 85 to 170 €/kW. This value was attributable to a reduction in the standing reserve required from conventional plant and in terms of reduced carbon dioxide emissions.

The overall conclusions are that:

- Variable renewable energy sources such as wind can replace energy from conventional sources of power generation but cannot completely replace requirement for the conventional plant to be present to meet power demands, if system security is to be maintained;
- Energy storage at the network scale can potentially supply a range of services to the electrical energy market – one such service is supplying bulk energy storage that could allow a certain quantity of conventional plant to be removed;
- Energy storage can be of benefit if it can demonstrate that it can (1) supply a range of energy services and (2) provide significant levels of ‘firm’ power when combined with a network having a significant intermittent renewable energy penetration at an economic cost. If not it will be cheaper (although less potentially beneficial) to meet the plant security margin by maintaining or building additional conventional generating capacity.
- An important consideration in using storage to firm-up intermittent renewable energy supplies is the quantity of storage provided in a given application. While storage has potential advantages over peaking plant and standby generation it has one potentially major drawback: its energy output is finite; once its stored capacity is exhausted it is useless until its next charge cycle. This is a major difference from other plant that is only constrained by the availability of a fuel stock at the power station site. The optimisation of the size of a store for a given application is a key consideration for any application – increased storage increases costs – but too little provision can severely limit the usefulness of the store.

In summary, network-scale energy storage does not have to be a requirement for delivering the EU renewable energy targets. However the development of a range of cost-effective flexible energy storage systems is likely to allow the delivery of the RES targets at a reduced overall cost and with enhanced network flexibility.

5.1.3 Regulation of the Energy market

Electrical storage systems can bring a range of benefits to the actors in energy markets. These benefits can accrue to generators (from large scale through to domestic), distribution system operators, transmission system operators and suppliers (wholesalers).

To optimise the commercial returns on a storage system investment potentially requires agreements with all the above actors, introducing a series of possible constraints and risks in maximising the realisable values from a storage system.

Storage plant can supply the following services⁸, the groupings being linked to the time periods over which they operate – the first being of the order of seconds or less, the second being minutes or parts of an hour and the third being generally longer term, parts of an hour through to fractions of a day or possibly longer:

- Power Quality and Power Management
 - Preventing voltage dip
 - Preventing cascading grid failures

⁸ See the Glossary section for a description of these issues listed below.

- Trading to Optimise Tariff Income
 - Peak Shaving
 - Removing the need to incur imbalance charges
- Energy Storage to firm up Intermittent Renewable Energy
 - Improved dispatchability
 - Reduces the requirement for conventional generation as ‘back-up’
 - Provides flexibility in operating the renewable generator and the local grid

Each of these can be potentially be expressed in terms of a monetary value per MW of export/import capacity (UK DTI 2000).

The values of the various services that a storage system can supply are also dependent on the regulatory structure and the design of the energy and electricity market in a given country and state and the degree of regulatory risk. The case already cited in Section 1 is an example of this. Pumped storage in the England and Wales system could realise very large rewards in the early period of the New Electricity Trading Arrangements (NETA) in 2001 however as the regulator modified the market structure and rules to reduce the differential between the system buy and system sell price for electricity the value of pumped storage fell and plant was even mothballed. This illustrates that while storage has a value it can be highly dependent on market structures and possible changes to these structures. This will affect the willingness of investors to consider storage.

Considering electricity network energy storage in the context of the commonly used electricity market systems, the following general conclusions can be drawn.

In *pool based systems*, there is no requirement for advance generation commitments and all generation attracts the same marginal price. In such systems there is little potential for the combined operation of storage and a renewable generator – while the presence of an energy store has an inherent arbitrage value it cannot in this type of market system provide additional value over and above that from the renewable generator itself. The network operator would be managing the risk from the intermittent renewable.

However, in markets such as that in the UK at the present time, there is a requirement for *advance notification of generation schedules and imbalance penalties for failure to reach specified dispatch*. The value of a combined generator and storage in this case is dependent on the forecasting capability of the generator and the magnitude of the imbalance penalties that can be avoided. In this case there is potential value to the generator in firming up the output and making it dispatchable.

Another market type is one based on *fixed price, fixed volume contracts*. In this case intermittent renewable generators have very low value as there will be little demand for their non-dispatchable output. The value of a combined operation of an energy store and a variable renewable generator can provide a benefit in this case, the value of which will depend on the daily price variation and imbalance penalties.

In summary the potential value that energy storage can offer to an intermittent renewable generator is highly dependent upon the market environment in which they are operating.

- In a pool-based system the combination of an intermittent renewable and storage to provide dispatchability will not realise any additional value to the generator.
- For markets such as in the UK or the Nordpool, that require advance notification of output and provide for imbalance penalties, the value of the combined outputs from the store and generator depend on the forecasting ability of the operation and the magnitude of the imbalance penalties that are avoided but there is a potential advantage to the generator as long as the additional value realised by making the output dispatchable exceeds the cost of the storage facility.
- In a market based on fixed price and volume contracts the inherent value of intermittent or variable renewables is very low. The value of the combined storage and renewable generator plant is in this case determined by the variation in daily prices (i.e. the spread between the highest and lowest system buy and sell prices) and the imbalance penalties that may apply. As in the previous case, the combination of intermittent renewable and storage can potentially be beneficial to the generator if cost criteria can be met.
- It is also the case that for markets with a requirement for advance notice of outputs the lead time between notification and market closure can often be shortened as operational experience with the market is accumulated. This shortening of time is however not beneficial to the wind storage combination as it makes the predictability of the renewable generator an easier proposition and therefore reduces the additional value from the store.

5.1.4 The Influence of Renewable Energy Support Mechanisms

An additional but very important issue for the development and value of storage is the effect of Member State renewable energy support measures and incentives. In the UK, Ireland and a number of other countries with more liberalised markets the energy from a renewable generator is valued separately from the 'green' incentive. In the UK for example, Renewable Obligation Certificates ('ROCs') are given to eligible renewable generators for every MWh of energy they sell to a licensed electricity supplier. The electricity is valued separately from the certificate (in the present UK situation the electricity has an average value of around 5 €/MWh while the ROC has a value of 8.5 €/MWh, giving a total value of 13.5€/MWh).

In many European countries the preferred support mechanism is the 'Feed-in Tariff'. This mechanism provides a guaranteed price for the energy from a given technology. In Germany for example, the feed-in tariff laws provide a price of around 8 €/MWh for wind energy. This price is for the electricity and the 'green' benefit.

The key issue here is not the price but the different nature of the support mechanisms: in the UK system the generator must still find a market for the electricity, trading it as he would any other electricity from a traditional generator such as coal, gas or oil. In the German system the supplier is obliged to take the electricity (under the so-called 'must-take' form of contract) and pay the feed-in tariff price. Therefore in the UK system the generator is incentivised to 'firm-up' the energy he supplies to the supplier to increase its value and ensure a buyer, whereas in Germany the generator has no incentive to invest in storage to firm-up the energy supply, he gets the 'feed-in' tariff whenever he supplies energy whatever the system demand and supply situation.

In Germany (and other countries with feed-in tariff) it is the network operator or supplier who would be incentivised to invest in storage to manage the imbalance of supply and demand.

There are difficulties stemming from the feed-in tariff structure and its effect on the market actors who would benefit from storage. Network operators are generally not encouraged to operate generation plant. Storage is likely to be treated as generating plant and therefore in many systems in Europe the present legislated market structure is likely to be a barrier to the development of storage – the generator has no interest in investing and the network operator - should he be interested - may well find the legislative structure against him.

The **key messages** from this section are:

- Governments and Regulators need to have a clear appreciation of the potential benefits of storage in delivering sustainable energy systems.
- Governments and Regulators must take these into account in designing and implementing policy and regulatory frameworks.
- The economics of network electricity storage are highly dependent on the type of market, the manner in which the market is regulated and the form of the renewable energy support structure applied.
- There is potentially a very high degree of policy and regulatory risk for developers of energy storage in this area.
- This risk needs to be recognised and addressed if suitable storage devices are to be brought to the market and tested on an equitable basis.

6. POLICY CONCLUSIONS AND RECOMMENDATIONS

This report has reviewed the status of energy storage technologies from technical, economic and regulatory perspectives, to establish how they can contribute to addressing the EU's key policy challenges of energy security, RES deployment and greenhouse gas emissions reduction. We have focussed on energy storage for electricity networks and their operation - particularly in terms of the management of networks with large percentages of intermittent renewable energy generation - and for transport.

6.1 Conclusions

Our conclusions are that:

- Network-scale electricity energy storage does not have to be a requirement for delivering the EU renewable energy targets. However the development of a range of cost-effective flexible electricity energy storage systems is likely to allow the delivery of the RES targets at a reduced overall cost and with enhanced network flexibility;
- Energy storage technologies can help to improve the EU's energy security provided that they can genuinely assist wider renewable energy deployment;
- Currently the European electricity market remains fragmented. The inconsistent operational and regulatory approaches, and different markets, have variable consequences for energy storage. The result is a lack of clarity on who is responsible for bringing forward energy storage technology solutions and whether they should be at the project level, the network level or a combination of both solutions;
- The necessary operational management and regulation of electricity networks across the EU is likely to place energy storage technologies at a disadvantage unless their value within these networks clearly exceeds their costs. At present there is little practical experience or knowledge of how energy storage technologies might be valued within these networks. There are therefore significant barriers for a developer of a network electricity energy storage device in realising revenue streams from the various benefits a device can potentially deliver;
- The present wide range of renewable energy support mechanisms being applied in the EU affect the way that the costs of managing intermittency are attributed within the energy market. In some Member States these costs fall on the generator, in others on the system operator or wholesaler. This creates additional uncertainties on how investments in energy storage might best be made.
- Energy storage technologies for the transport sector are already a cost-effective solution for some applications. Application of these technologies in the transport sector can be expected to increase in the face of high fuel costs and an increasing emphasis on European emissions regulation through voluntary or other means;
- The deployment of hydrogen-based systems for storage should remain a long-term goal within the electricity and transport sectors.

6.2 Recommendations

The above conclusions lead us to suggest the following recommendations, designed to assist energy storage technologies to provide maximum benefits. These recommendations are:

For Electricity Network storage

- European research on energy storage should be more clearly focused on the key technologies (identified in Section 4 of this report) and should - where practical - take greater account of key issues related to the eventual deployment of the technologies (identified in Section 5);
- We support and endorse the Commission's proposal (COM(2007) 723 final) for a European Electricity Grid Initiative and recommend that this initiative should also be used to support a specific strand of European research which would aim to encourage integration of energy storage into electricity networks;
- Work should be undertaken to confirm possible options for the stable operation of European electricity networks with very high penetrations of renewable energy (and possibly nuclear generation) in line with the 2020 and 2050 energy targets. This work should assess the quantity of storage and/or reserve generation that would be desirable and achievable under a range of scenarios for intermittent generation and the development of European transmission systems. Active participation of utility companies in this work is highly desirable;
- In view of the
 - significant market and regulatory barriers to accessing the full value of an electrical energy storage device embedded within an electricity network;
 - possible key role for storage in enabling cost effective renewable energy exploitation; and
 - scale of the EU 2020 and 2050 energy targets;the EU should investigate ways of supporting and monitoring trials of demonstration network scale electricity energy storage devices to allow the benefits to be confirmed;
- Work should be conducted to assess the impact of electricity network management and regulation requirements on the future prospects for energy storage. This work could be used to
 - help guide future research and development priorities; and more importantly
 - raise awareness of energy storage's benefits and issues with network operators and regulators across the EU Member States;
- The effects of renewable energy support mechanisms on electricity energy storage should be assessed. The objectives of this study would be two-fold:
 - to develop measures that could provide confidence to those investing in storage that they will be able to realise benefit from their investment;
 - to make policy makers in renewable energy aware of the issues surrounding electricity energy storage and the influence of policy measures on the potential electricity storage market;

For Transport

- EU research support should continue to reflect the long-term goal of hydrogen-based systems for storage making a major contribution to the electricity and transport sectors;
- The wider deployment of existing BEV and HEV energy storage technologies across the EU should be monitored, and should be encouraged in Europe-wide dialogue with vehicle manufacturers.

ANNEX 1 – GAS STORAGE

The European gas market has changed significantly over recent decades. Of the EU25 countries 23 are natural gas importers. Between 2004-2005 indigenous production decreased by 6.9% whilst the primary energy consumption of natural gas rose by 1.4% (Eurogas, 2005). In summary the EU is becoming more dependent upon imports which will be supplied via pipeline from Russia or through increasing LNG (Liquefied Natural Gas) imports. Adapting to this changing situation requires an increase in gas storage particularly where resources are being supplied through LNG. In addition sourcing gas from a number of specific regions makes many of the EU countries vulnerable in terms of security of supply.

Security of supply is becoming more important as indigenous EU energy supplies decline. This change is occurring at the same time that Europe is increasingly relying on natural gas for power generation. Recent work undertaken on energy security (AEA E&E, 2007) has raised a number of important issues which are important to consider:

- The EU is moving towards regional energy markets;
- Stability of distribution components, such as compressor stations and interconnectors, was often more important than individual power stations;
- Oil presently has a greater security of supply than gas and electricity as EU legislation requires Member States to store 90 days worth of oil supply. This is perhaps an issue when one considers the shift away from oil fired power generation capacity.

EU Growth

Natural gas is becoming an increasingly important component in European Community energy supply, and, as indicated in European policy approaches (European Commission, 2004; European Commission, 2007) the EU is expected in the longer term to become increasingly dependent on gas imported from non-EU sources of supply.

At the end of 2005, the total number of gas customers connected to the EU25 grid rose by 1.5% in comparison to 2004, reaching 103 million customers. Furthermore, EU25 natural gas consumption has risen at a steady pace representing an increase of 1.9% between 2004 and 2005. Southern EU countries register well above average developments in their consumption levels. Spain registered the largest market growth, with 17.7% increase between 2004 and 2005, followed by Portugal (12.6%), Italy (6.9%) and Greece (6%). Outside the EU25 Turkey has registered the most dramatic growth, with a 21% increase in consumption between 2004 and 2005, equally distributed amongst the different sectors and resulting from new gas distribution lines becoming operational. Total supplies to EU25 (indigenous production and imports) amounted to 413.6 Mtoe, and were higher than consumption, the difference being injected into the storage facilities.

The largest proportion of gas supplied in the EU25 comes from indigenous production, covering 42% of the total net supplies in 2005. The main external source of supply is Russia with 24%, followed by Norway with 14%, Algeria 11% and 9% for “other sources” (including amongst others Egypt, Gulf countries, Libya, Nigeria, Qatar and Trinidad Tobago).

The majority of the countries in the EU (except perhaps Denmark, the Netherlands and the United Kingdom) remain dependent on gas imports. Unlike electricity, this situation will not change in the short term as it is primarily linked to the existence of natural gas resources in the country's territory (or their respective continental shelf).

The degree of interconnection between Member States is usually relatively high, but depends also on historical supply patterns. Some Member States, such as Spain, are relatively poorly connected to the European network due to the fact that most of its supplies are delivered from the Maghreb region both by pipeline and LNG. Furthermore, the Baltic States and Finland are not yet connected to the European grid, a fact that is likely to be improved, once economic conditions allow. Similarly, Greece is not served by a pipeline connection to other EU Member States, though the situation may improve once the energy market in the Balkans becomes a reality.

Gas Storage

Natural gas storage is well known and has been used for several decades to provide a quick, safe form of flexible gas supply for short-term requirements such as peak shaving and parking purposes and it is becoming increasingly important for enabling the effective operation of the modern gas supply system. Storage is used as a tool for providing flexibility in gas supply to accommodate demand variation and to cover risks in relation with security of supply: withdrawals from storage facilities are the major source of temporary additional gas supply.

Storage contributes to mitigation of the impacts of seasonal swings in demand. In addition, as most European countries are strongly dependent on imports, storage may also be used to maintain gas reserves to protect customers from interruptions (ERGEG, 2006). As gas demand is growing in and outside the EU, the availability and cost of gas storage facilities becomes an important element for the functioning of the internal market in natural gas.

However, natural gas storage is much more expensive than oil storage. The costs and benefits of creating potentially expensive safeguards against low probability supply interruption events require careful analysis, as well as agreement on who will pay for such measures (Stern J, 2004).

The EC is already considering the development needs for natural gas storage facilities at a European level through the Trans European Network – Energy programme. The status of the programme was reviewed in 2005 within the TEN-E Invest report (TEN-E, 2005)). This indicated the existence of over 100 gas storage facilities in EU30 at that time. The total maximum working volume of the EU30 gas storage facilities was 77 bcm, and the maximum withdrawal capacity is 1.5 bcm per day.

Expected investment in storage facilities up to 2013 ranges from 4 to 10 €billion and to 2023 the range is from 5 to 22 €billion. These investments would increase storage capacities by between 9 and 26 bcm by 2013 and by 12 to 56 bcm by 2023.

Outlook

In Europe, the future investments in the current infrastructure will mainly be in rehabilitation and maintenance of the system. Replacement of old capacity will be less costly than replacement of a newer gas transmission capacity would be. Several transmission service operators (TSOs) have reported that there were significant saving potentials in modifying or changing the compressor stations, which may also be required if stricter environmental legislation is introduced.

Greater pipeline interconnection between EU Member States, and between external suppliers and Member States, is feasible and in a number of cases affordable. The EU has extended a significant volume of concessionary finance for interconnections. Nevertheless, it will be difficult and expensive to introduce a major new source of pipeline supply unless large-scale transit of Central Asian gas via Russia can be arranged.

Some diversification is feasible and affordable by increasing imports of liquefied natural gas (LNG). Costs throughout the LNG chain (liquefaction, shipping and re-gasification) have fallen sharply over the past decade and this trend is anticipated to continue.

LNG Market

LNG is largely traded directly between producer and consumer nations, both of which are increasing in both number and volume. The biggest LNG consumer nations are Japan and Korea, but Spain's consumption makes it the fourth largest consumer in 2004, just after the USA.

LNG supply tends to be governed by long-term (~20 year) sales purchase agreements and there is relatively little overall flexibility in the market. Some spot cargos are available due to uncommitted early production of LNG trains as production is ramping up but this may not continue indefinitely. However, with both larger supply and demand, the spot market is likely to increase. The supply of LNG ships is limited, with most tied to particular routes. However, European LNG supplies generally come on short shipping routes from North Africa at present.

Several EU Member States derive a large proportion of their gas supply from LNG; in particular Spain and Portugal. Portuguese LNG imports rely on a single terminal but the overall consumption is modest. Spain has a much higher consumption but imports through four terminals.

LNG Outlook

LNG is taking an increasingly important role in world energy supply and the numbers of liquefaction and re-gasification trains are increasing together with the numbers of LNG carriers. Changes are predicted with large receipt and re-gasification facilities being planned and constructed in the UK and Italy in particular. Large liquefaction facilities are currently under construction, particularly in the Middle East and further large facilities are under consideration.

The security of supply aspect for LNG from an EU perspective is purely dependent upon source country which has the advantage over piped gas in being not dependent upon a particular source. However - environmentally - LNG is more energy demanding in its production and transport process which negates some of the emissions benefits realised by piped natural gas.

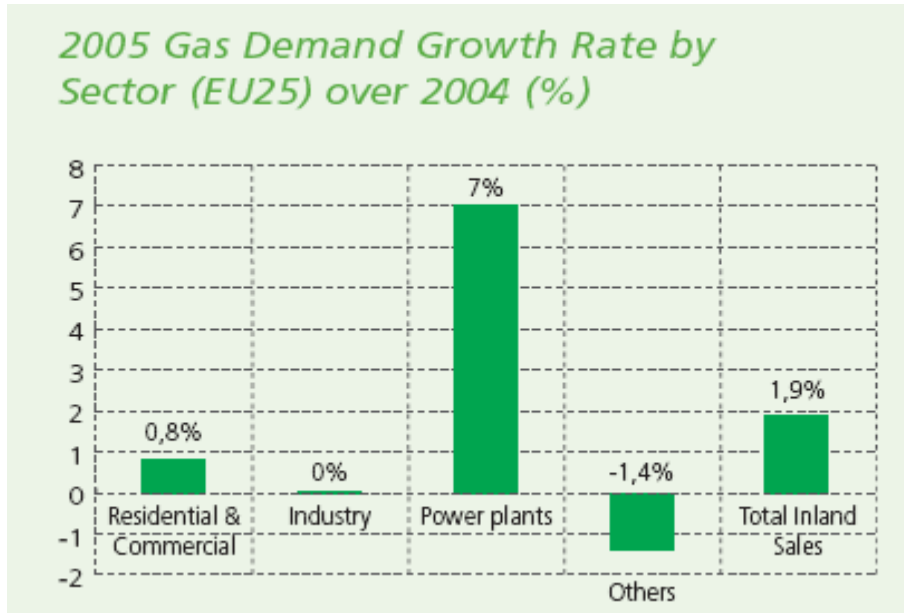
Natural Gas and Electricity Storage

There are a number of areas where the relationship between natural gas and wider energy storage issues could be important:

- Natural gas is becoming increasingly important as a source for power generation consuming 23% of total gas across the EU in 2005 (Eurogas, 2005) (see Figure 12). Therefore gas can act as an important alternative to electricity supply in the EU whilst also posing a significant risk to supply should there be shortages in production and supply;
- Gas power generation could be easily integrated with fluctuations in renewable production. This is dependent upon storage technologies being able to match demand for the start up time of a CCGT;
- In the future, changes in costs may perhaps make it worth investigating gas storage versus CAES alternatives for specific sites. Dependent upon future trends of gas storage a large number of potential sites could be converted to CAES.

- Research is therefore required into the costs and benefits from gas storage versus CAES into the future;
- Reductions in indigenous supply will create an increased dependence on imports from outside the EEA.

Figure 12: Gas Demand Growth Rates in EU25



(Source: Eurogas, 2005)

Summary

Increasing LNG imports to the European market mean the greenhouse gas emissions associated with natural gas will increase. LNG is more energy intensive as it requires cooling to a certain temperature.

Security of supply is an issue for gas with a greater dependency on non-EU countries for supply. Increasing the number of gas storage sites is also a safety/security risk. Gas stores are not able to store the same volume as oil. EU regulations stipulate that countries must store 90 days worth of sufficient oil supplies but the gas market has no such requirements.

As mentioned previously CAES plants require the same sort of underground caverns as for gas storage, meaning that CAES and gas are in competition for suitable sites.

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GLOSSARY

‘Black Start’ Capacity: All large power systems require some contingency arrangements to enable a restart in the unlikely event that all or part of the system shuts down. The process of restoring the power system is commonly referred to as Black Start. This entails isolated power stations being started individually and gradually being reconnected to each other in order to form an interconnected system again. Not all power stations have, or are required to have, this Black Start capability. Power stations that do have this capability may be recognised by the system operator and be financially credited for offering this service.

Bridging Power: An area of the Discharge Time vs. Power Rating graph (see Figure 1) where both energy management and power quality issues are important.

Cascading Grid Failures: The network operator often requires as part of its regulations that local generators disconnect from the network when they sense network faults. This is to avoid such generators continuing to energise the local network if a fault remains present and providing the potential to cause further damage or potential loss of life. However if the local generator can sense the fault and ride through it (if it is only of a short time interval) this can be beneficial in maintaining supply. Fast response energy storage devices can in principle meet this requirement and avoid ‘cascading grid failures’ where a series of generators switch out causing a domino effect and leading to a local or more wide spread black out.

Charge/Discharge Lifetime or Charge / Discharge Cycles: Measures of how often storage technologies can be “re-charged” without significant degradation of their storage capability.

Demand Side Management: The process of managing electricity demand to best fit with technical and economic ability to supply at different times of the day and year.

Discharge Time: The period of time over which an energy storage technology releases its stored energy.

Dispatchability: The degree to which a generator can forecast its output ahead of time. A conventional generator can generally guarantee to provide energy and power to well-defined values well ahead of a fixed point in time. Wind generators on the other hand cannot forecast their output with any accuracy more than a few hours ahead of time. They are therefore regarded as less dispatchable or even non-dispatchable.

Energy Density, Charge Density or System Energy Density: The amount of energy that can be supplied from a storage technology per unit weight (measured in Watt-hours per kg, Wh/kg).

Energy Management: The concept and practice of decoupling the generation of electricity from its instantaneous consumption.

Imbalance Charges: An alternating current network must be continuously balanced in terms of power supply and demand. Generators that cause unpredicted imbalances in supply (by over- or under-generating compared to their agreed or forecast generation profile) are liable in a number of markets to what may be punitive imbalance charges. The presence of a suitable storage device can allow the generator to avoid such charges by smoothing the generator’s output.

Load Levelling or Peak Shaving: An aspect of Demand Side Management relating to the minimisation of peaks in electricity demand (which are typically expensive to manage)

Peak Shaving: The network operator has to hold sufficient reserve capacity to meet any peaks in demand on the system, or have the ability to ask demand customers to switch off to

reduce the peaks. The generators that can supply this fast response peaking power are generally well rewarded and conversely the cost to the network operator of meeting such peaks is high. A suitable energy store can 'shave the top' off such peaks and remove the need for conventional fossil fuelled peaking plant to be present on the network.

Power Quality: The "quality" of electrical power supplied to consumers, typically defined by reference to issues such as lack of voltage fluctuation and lack of harmonic distortions.

Regenerative Braking: The process of extracting energy from the braking process in (e.g.) a Hybrid Battery Electric Vehicle.

Spinning Reserve: Power stations within an electricity grid system used to provide a back-up for power quality reasons. Such stations can respond within very short time periods and are rewarded by the grid operators for this.

System Power Ratings: The relative size of a power producing device or energy storage device, measured in units of Watts.

Voltage Dip: Starting of motors etc causes disturbance on the local network that are detrimental to the stable operation of the network. The presence of wind turbines generally exacerbates the effect. A suitable quick-response energy store can mitigate this effect.

ABBREVIATIONS

AFC: Alkaline fuel cell

UPS: Uninterruptable Energy Supply

BEV: Battery Electric Vehicle(s)

CCGT: Combined-cycle gas turbine

CO₂: Carbon dioxide, the main greenhouse gas

DG-TREN: European Commission Directorate-General for Transport and Energy

DMFC: Direct Methanol fuel cells

EC: European Commission

FCV: Fuel Cell Vehicle(s)

FP6: Sixth Framework Programme

FP7: Seventh Framework Programme

HBV: Hybrid Battery Electric Vehicle(s)

ICE: Internal Combustion Engine

IEA: International Energy Agency

ITRE: European Parliament Committee on Industry, Research and Energy

LNG: Liquified Natural Gas

MCFC: Molten Carbonate fuel cell

Na-S: Sodium-sulphur battery

NETA: New Electricity Trading Arrangements (applying within the UK)

OCGT: Open Circuit Gas Turbines

PAFC: Phosphoric Acid fuel cell

PEM: Proton Exchange Membrane fuel cell

R&D: research and development

R,D&D: research, development and demonstration

RE: Renewable energy

RES-E: Renewable energy electricity

SMES: Superconducting Magnet Energy Storage

SOFC: Solid Oxide fuel cell

TSOs: Transmission Service Operators

Energy and other units

atm: Pressure in atmospheres

bcm: Billion cubic metres

bn: Billion

GJ: gigajoule, 10^9 joules

GW: gigawatt, 10^9 watts

J: joule

ktoe: kilotonnes oil equivalent, the same amount of energy as in 1000 tonnes of oil.

kW: kilowatt, 1000 watts

kWh: kilowatt hour, a measure of energy equivalent to the expenditure of one kilowatt for one hour.

l: litre

M: million

Mtoe: million tonnes oil equivalent, the same amount of energy as in one million tonnes of oil.

MW: megawatt, one million (10^6) watts

t: tonne

TW: terrawatt, 10^{12} watts