Energy transmission distribution and storage

Materials UK Energy Review 2007

Report 5 - Energy Transmission, Distribution and Storage

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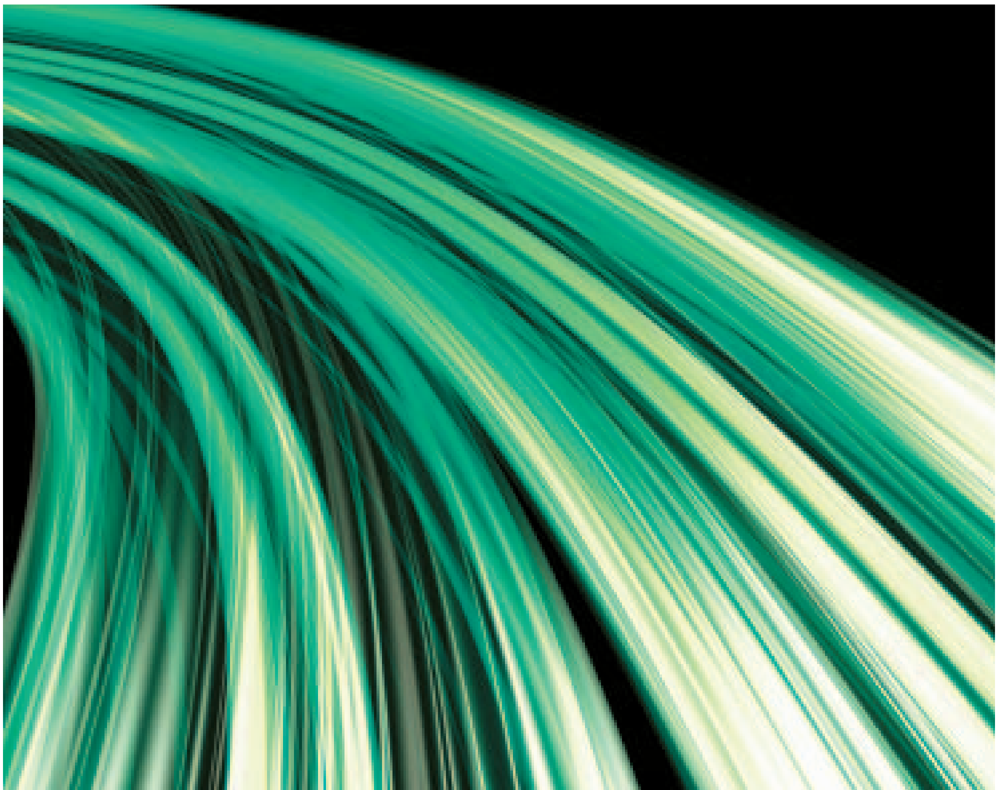
1.0 Executive summary

This report addresses UK R&D priorities for Energy Materials in Transmission, Distribution and Energy Storage (TDES).

The Report

- Outlines current opportunities and challenges that face the TDES sector
- Identifies market trends, barriers, drivers, and future technology requirements
- Identifies the innovative materials developments that are crucial to deliver a cost-effective and sustainable future energy infrastructure.

Advanced functional and structural materials are critical to reducing the UK energy sector's impact on the environment whilst also improving efficiency and reliability. This report recommends an integrated programme of Energy Materials R&D to improve still further the benefits that innovative materials and process technology can deliver.



Recommendations

General Recommendations:

- UK knowledge in energy materials for transmission, distribution and storage has become dispersed since privatisation of the energy services. There is a need to collect the available data and capture the experience of mature practitioners before retirement. Such information should be collated and stored, together with more recent R&D (such as the EPSRC Supergen programme) into a coordinated national TDES archive, possibly located at the recently announced Energy Technology Institute (ETI) at Loughborough University
- The TDES sector believes that current asset updating programmes should be coupled with R&D to ensure that the UK has an efficient and sustainable energy system to meet future needs. Over £500M p/a is being allocated to upgrading the UK electrical transmission infrastructure. This opportunity should be used to incorporate some of the major technological improvements currently being developed [such as SuperGrid and associated 'smart energy' systems].

Innovative engineering design and materials R&D is required in the following areas:

Electrical Transmission and Distribution

- Materials technology provides a 'twin track' approach to future enhancement of the transmission and distribution network. Materials developments are identified that will provide low cost incremental developments to existing facilities, thereby enabling useful improvements to be made in energy efficiency.
- More ambitious 'disruptive'/'step-change' materials development could however literally transform the electricity infrastructure. Recent developments in High Temperature Superconducting (HTS) materials would allow the electricity network to carry power through 'negligible loss' cabling from power stations to consumers with little, if any, 'step up' or 'step down' transformation. Networks could also be protected using fault current limiters that exploit the particular characteristics of HTS materials. USA & Japan are currently converting such materials science into practical equipment. The UK also has the technical skills. This report recommends that the UK builds on existing expertise to generate a series of 'technology demonstrators' to stimulate industrial involvement.

The various materials options for both incremental improvement and 'step change' advances are outlined below:

Electrical Equipment

Incremental Technology:

- Research on materials technologies to support the application of wide-band gap semiconductors in electrical transmission and distribution for high power switching
- Development of more compact, less intrusive switchgear. Large clearances are currently necessary to withstand high steady-stage voltages, together with large volumes for arc extinction. Improved material and engineering options could significant reduce the bulk.

1.0 Executive summary

- More environmentally friendly dielectric materials are also required to replace the arc suppressant SF6, which is a greenhouse gas.
- Smaller, quieter and less 'lossy' transformers require transformer core steels that support high flux densities without loss or noise. Such steels will require enhanced coatings to aid noise reduction, offer component protection and extend lifetimes.

'Step change' Materials Technology

- Development and demonstration of superconducting fault current limiters using existing High Temperature Superconducting (HTS) materials and process technology. Development of new HTS materials is a longer term R&D requirement. The superconducting limiter can act 'instantaneously' thereby protecting even sensitive computer facilities from millisecond to major 'outages'.

Structural Materials

- Overhead power cables and local distribution wires are visually intrusive. Higher strength conducting wires / cables with reduced 'sag', particularly when warm, together with fittings that can run hotter, would enable overhead cables to carry more power with shorter insulating strings and within a lower silhouette. Future upgrading could include the introduction of 'no loss' superconducting cables.

Transmission of other Energy Fuels

Emphasis has so far concentrated on electrical transmission and distribution. There are alternative energy fuels (oil, gas & hydrogen) that require transportation and distribution. The materials R&D associated with transmission of such fuels includes development of:

- Higher strength and toughness pipeline grades of steel and a fuller understanding of microstructure and properties. Clad / composite pipes will also be introduced.
- More economic corrosion-resistant pipes for mixed gas and hydrogen transport combined with greater understanding of the metallurgical factors involved in mixed natural gas and in hydrogen transportation along current pipeline materials.
- Lower cost cryogenic materials for Liquid Natural Gas (LNG) transmission and liquid hydrogen storage.

Electrical Energy Storage

'Portable power' requires energy to be carried in a variety of forms - from the ubiquitous battery packs, through intermediate sized storage for hybrid automotive power, to large scale devices that can store gigawatts of power. Again the range of technologies covers incremental developments in relatively long-standing storage methods to more ambitious 'step change" developments:

Incremental Battery Technology

- There is need to develop superior secondary lithium cells using chemistries that do not rely on strategically sensitive cobalt additions. The issue of recycling / disposing of a wide range of complex battery materials also needs addressing.
- Flow batteries / fuel cells require 'scaling up' with an emphasis on efficiency and environmentally acceptable operation. Again recycling and disposal are issues.

'Step change' Storage Technology

- High-energy storage supercapacitors are being developed to 'demonstrator status' for hybrid drive regenerative braking systems as part of EU programmes. Similar supercapacity storage methods would allow full exploitation of fluctuating energy generators [e.g. wind turbines].
- Superconducting Magnetic Energy Storage systems (SMES) provide high storage and release capabilities over a wide range of energy levels. Future commercial opportunities look promising. A range of innovative materials research studies associated with superconducting and conventional magnetic energy storage systems are identified.

Priorities / timescales for more specific materials R&D are given in the text and at the end of this report.

2.0 Introduction

This report summarises the R&D priorities for materials used in energy transmission, distribution and storage. It also identifies future commercial and developmental drivers, market trends, current state of the art and future prospects.

Considerable interest has been shown worldwide in materials for energy applications. The technologies that ushered in the 'electronic age' of information technology, and widespread mobile communications are now being applied to the management of complex electricity networks. The phenomenon of 'high temperature' superconductivity finds application in the protection of high voltage power lines through fault current limiters, while electrical storage exploits supercapacitors and superconducting magnetic energy storage. Most of these recent developments are dependent on the latest innovations in materials and processes. The burgeoning area of nanotechnology offers further opportunities to 'make a material difference' within the power sector.

Portable power (e.g. electrochemical batteries, fuel cells), sometimes in combination with other power sources (hybrid power), enables individuals to communicate and work (via mobile phones, laptops etc) while 'on the move'. These are further examples where functional / electronic materials for energy have made a dramatic impact on our lives.

Conventional structural materials are also critical to the transmission, distribution of storage of energy. Although lacking the glamour of their functional/electronic counterparts, structural materials are the 'building blocks' of the energy infrastructure. They are used in the vehicles (land- and sea-based tankers) that transport energy fuels (coal, oil, gas and hydrogen) and they provide the static pipework and containers through which much of the nation's fuel is carried and stored. Transformer steels are used in the conversion of power to different voltage and current levels, while cabling/wire is used both overhead and underground to carry electricity to consumers. Many of these structural materials are well established. However, recent material innovations include lightweight composite structures for pylons and fuel storage, materials for cryogenic applications and exotic chemical compounds that absorb and release large quantities of gaseous hydrogen. All such 'energy materials' are considered here.

3.0

UK Electrical transmission and distribution system

The UK Energy Review [ref.1] sets out two major priorities:

- Security of supply
- Emissions reductions

This overview discusses some of the technical challenges facing electricity networks in the light of these priorities.

Electrical Power Generation: Current Status

The UK currently generates some 40 gigawatts (GW) of power, which increases to 60GW at peak times. By 2015 a further 15GW of extra power will be needed. That power is currently delivered from 30 large (>1GW) coal, gas and nuclear power stations.

The generated power is transmitted nationally across an extended network ("the grid") and is then distributed to users via local distribution networks.

An extra 50% (20GW) of power is generated just to accommodate occasional large surges in power. That huge increase in capacity could be minimised, or even eliminated, if the transmission and distribution networks were more effectively managed. Technology is becoming available that will allow such management, both centrally and at the local distribution level:

Electrical Transmission and Distribution Networks: Current Status

The UK transmission network transmits 'high voltage' (275kV) electricity from power stations to regional distribution networks via some 25,000km of overhead cables. High voltage transmission helps minimise energy loss over these large distances.

Regional networks then redistribute the electrical power to local industrial and domestic users via some 800,000km of 'lower voltage' (132kV) overhead and underground cabling. Local substations transform that power to 240volts for domestic use. It is at the regional level that small-scale generators will be able to feed power back into the system.

Under conditions of average loading, estimated energy losses from transmission and distribution are about 2% and 6%, respectively The losses occur when the electricity is 'transformed' from one voltage/current combination to other and during conduction through the many miles of wires and cables. Losses are greater at the higher loads. The total 8% energy loss equates to about 3.2 GW of power. This is equivalent to about 8 million tonnes of CO_2 entering the atmosphere from a coal fired power station or 2.5 times the output from a Sizewell B nuclear reactor. All to no useful purpose. Engineering solutions will exploit high-power wide-bandgap semiconductor switching.

Bottlenecks limit the total power that can be transmitted across the network. Net flow, from the North to the heavily populated South, is limited to 2.2GW. There is a single point of interconnection between the UK transmission grid and Europe (2GW). There is also an Interconnection with Northern Ireland (0.5 GW). To maintain security of supply there is need for much greater interconnectivity at both the transmission and distribution stage. Engineering and materials solutions are identified [later].

Electricity consumption rises with increasing population and growing wealth. This presents challenges to local distribution networks. As components in the network approach maximum capacity, risks of faults and high-energy losses increase. There is a growing need to such control faults in both high voltage and medium voltage systems. High temperature superconducting fault current limiters offer a potential solution.

A substantial asset replacement programme is underway to upgrade current ageing transmission and distribution networks. Such a programme offers the opportunity to introduce new technologies to improve reliability, flexibility and cost-effectiveness. Current upgrading programmes include £560M for the 'Beauly-Denny' line in Scotland, where transmission voltages will be increased to 400kV (£330M), together with £168M for upgraded twin transmission lines between England and Scotland. Further strategically important connection upgrades are also under consideration. [ref.2.]. UK electricity transmission asset replacement programmes currently average ~£500M p/a

3.0 UK Electrical transmission and distribution system

Building new transmission and distribution networks is both costly and difficult. Planning approval and civil engineering work can take years to implement producing supply bottlenecks and raising problems of security and power quality [ref.2]. For example, a new 96km line in Yorkshire required 2 public enquiries and took 9 years to gain planning consent. Such delays could be avoided if existing powerlines could be upgraded. Retrofitting high temperature superconducting cables offer a means of increasing system capacity. Implementation of distributed generation and energy storage could also assist in balancing future pressures on embedded distribution.

Greater use of sustainable power is a priority for the UK government [ref.1]. Technologies such as large offshore windfarms are more suitable for direct connection into the transmission grid whereas smaller-scale technologies such as combined heat and power require connection into distribution networks. Different connection modes require different materials solutions for integration, control and energy storage.

Globalisation

The last 20 years has seen extensive globalisation of the electricity transmission and distribution equipment business with UK companies businesses being integrated into larger groups with headquarters outside the UK. Globalisation has also led to rationalisation of manufacturing operations and a reduced range of equipment manufactured in the UK. This globalisation coincided with a period of relatively low investment in UK electricity transmission and distribution equipment and a greater focus on asset management and controlling new asset cost. To remain competitive, Western European companies have transferred manufacture of mature products to countries with lower labour costs. More recently this process has been catalysed by the need to manufacture equipment in China & India in order to win market share in these important growth areas. UK equipment manufacturers need to concentrate on 'high tech.' products, such as:

- High Voltage Direct Current (HVDC) and:
- Flexible Alternating Current Transmission Systems (FACTS)

UK manufacturers supply into this sector of the UK and export market in equal proportion.

The advantage of HVDC is the ability to transmit large amounts of power over large distances with lower capital costs and lower losses than AC transmission. An HVDC system can have half the loss per unit length of a high voltage AC system carrying the same power. Typical losses for HVDC are about 3% per 1000km. This technology is also better suited for undersea cabling, where high capacitance would cause large AC losses.
To date, nearly 100 HVDC projects have been realised covering over 25,000km. [ref.3] Current technology has suitable materials but further materials development would aid greater efficiency and higher power output.

Flexible Alternating Current Transmission System (FACTS) is defined by the Institute of Electrical & Electronics Engineers (IEEE) as a power electron based system, with other static equipment that provides control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability. A range of materials developments help to facilitate these more efficient networks:

Market Value

The UK market for electricity transmission and distribution equipment, excluding cabling, is about £1bn p/a, with a similar value invested in cables. About 15% of the equipment is manufactured in the UK with the rest imported from other EU states and beyond. Although one UK company produces oil-filled cables, traditional manufacture of cables / overhead power lines is from the Far East, while most modern designs are from Europe.

There is a global market in transformer equipment and in production of transformer core steels. Orb Electrical Steels, part of Cogent Power and owned by Corus is one of only 10 companies worldwide manufacturing transformer core steels. Turnover is £150M p/a. Corus Tubes & Pipes manufacture a range of welded pipes used in gas and oil transmission. Turnover is approximately £230M p/a.

Future emphasis should concentrate on 'high value added products'.

Current status of R&D

R&D in Electrical Networks

The European Union (EU) SmartGrids Technology platform has created a Future Vision for Europe's electricity networks that sets out a pathway for sustainable development. The Vision includes a robust transmission network with many points of interconnection across Europe, plus distribution networks that allow bi-directional flow with high levels of distributed generation and use of renewables. The proposed approach offers the opportunity to evolve networks that are more efficient and reliable than today whilst allowing integration of renewable power sources. This Vision has been adopted by the EU and high priority projects are being invited within FP7. Other supporting issues need to be addressed at national level as part of medium-term research agendas. Transforming the UK electricity grid into a SmartGrid would allow a significant reduction in energy losses. Such a change would present a number of materials challenges:

US is also moving towards a smart energy network in its Energy GridWise™ programme. The basis of the system is electronic intelligence [ref.4]. Information technology employed in electrical grid command centres is beginning to infuse electronic intelligence throughout the network. Individual electronic devices operated by their own intelligent software communicate information on operating status and needs to the network and in turn collect information on prices and grid conditions. Constant interactions between millions of smart agents result in a collaborative, rather than centrally managed, network which opens up new capabilities:

- The ability to precisely manage electrical power demand down to the residential level
- The ability to network vast numbers of small-scale distributed energy generation and storage devices

IBM are designing software and hardware for 'Internet-scale' integration with real time analysis of massive amounts of data that will flow through networks of smart devices. Whirlpool is working on 'grid-friendly'™ appliances that will:

- Curtail energy use on demand
- Share energy with other devices and:
- Provide detailed energy consumption information for owners

In Europe, Siemens has created a Decentralised Energy Management System™ that acts as a virtual control room for distributed generator networks to optimise electrical demand. Several pilot schemes are underway in Germany.

The British company EnerG manages 700 combined heat and power generators using its Distributed Intellect Monitoring System™, which provides real-time data to diagnose and pre-empt failures. ALSTOM also provides a range of products to automate power plants, transmission networks and local distribution systems. The UK 2006 Energy White Paper considered 'Smart Meters' but they lacked the sophistication of the US & EU systems.

The US Energy GridWise system will respond 'just-in-time' to changing grid conditions, thereby shifting demand out of peak periods. It is claimed that by 2020, flattening peak demand could defer or even avoid the need for 100GW of new US generating capability and associated transmission and distribution capacity. Such power savings represent $50bn or 200 large gas turbine plants.

Distributed power suppliers meet the need for super-reliable, high quality power in hospitals, data centres etc. Such facilities cannot afford even millisecond outages. Brief power fluctuations that cause domestic lights to flicker briefly would cause costly computer crashes. A major US bank puts the cost of such millisecond outages at its credit card processing centre at $100,000 per minute. [5]
The City of London also saw 2 major 'blackouts' in 2003 and 2006, which seriously affected commercial transactions and local underground services. For example, a typical one-hour disruption to the London underground costs £5-7M.

Materials R&D in Electrical Networks

Wide bandgap semiconductors are emerging as a critical technology to ensure that power electronic systems in the electricity network offer affordable integration of high levels of managed distributed generation into the grid.

Wide bandgap semiconductor materials typically with a band gap larger than one electron volt (1eV). They are used in high temperature power devices. An early version was the use of silicon carbide (SiC) as a lightning conductor. Such devices have a high resistance to conventional voltages but once a high voltage threshold is exceeded the resistance drops allowing lightning strikes to run safely to earth.
The silicon carbide in early lightning protectors was produced in pellet form. More modern wide bandgap SiC materials exploit well-developed silicon semiconductor wafer technology. Although pure silicon devices can be used for intermediate level voltage switching, their voltage blocking capabilities are insufficient to process gigawatts of power. Instead wide bandgap SiC or Gallium Nitride (GaN) are favoured for future high power FACT & HVDC applications. Wide bandgap materials also offer greater switching efficiency, higher reliability and reduced thermal management.

Gallium nitride has slightly improved intrinsic wide bandgap semiconductor properties over SiC but the advantages are likely to be insufficient to justify use of GaN in high voltage power devices. This is because SiC wafer technology is relatively mature, whereas no pure GaN wafers are commercially available. Instead GaN is grown on SiC wafers. SiC Scottky diodes are being marketed with twice the blocking voltage (600V) of Si diodes and SiC power devices in the kV range are being investigated.

3.0 UK Electrical transmission and distribution system

There remain semiconductor processing problems, but SiC is the most likely wide bandgap material for high power switching over the next 20 years [ref.25].

Over the longer-term (20-50 years) diamond wide bandgap materials offer most promise for high voltage power devices. Diamond is harder than SiC and therefore requires even higher semiconductor processing temperatures. As yet these processing issues have not been resolved. Some experimental diamond devices have been produced for sensor applications but no experimental power devices are anticipated in the near future [ref.25].

Materials research to allow affordable energy storage at the micro- and distribution grid levels is also of high importance. Further details are given in Section 4.

Transmission and Distribution Materials

Materials and sub-component suppliers in electricity transmission and distribution equipment have also become globalised. UK is now dependent on external supplies for much of this technology. There are however some areas where UK has maintained a global platform. E.g. Corus continues to manufacture & supply specialist steels worldwide

Most materials used in electricity transmission and distribution equipment are well understood and have performed reliably in national networks for decades. Some tradition transformer steels would however benefit from improved grain orientation and thinner strip to reduce power losses. There is also a need to reduce magnetostriction in order to minimise vibration and hence noise.

New multilayer dielectric nanostructures are being developed for insulators as well as capacitors and high temperature superconductors [see section 4]. Conventional dielectric materials are bulk metal oxides, polymers and ceramics. These materials can also be produced as dielectric layers with interspersed conducting layers but it is difficult to maintain sufficiently smooth interfaces between the layers to sustain high voltage stand-off values. Processes are needed that allow thin, smooth, fully dense, pure levels of alternate dielectric and conducting layers to be combined. Nanostructures produced by physical vapour deposition (PVD) are the favoured production route. A range of zirconia oxide, alumina and other nano-layered materials have been produced but further development is needed to achieve commercial production status and establish how best to incorporate such materials into UK networks.

Transformer Steels

Large transformers on transmission and distribution network are generally highly efficient (~95%). Even so, their losses contribute up to half the total losses within the grid network. More efficient transformers therefore justify continued development.

Improvements in electrical steels [also known as silicon or transformer steels] have led to transformer losses being halved since the 1970's. The transformer steel is usually cold-rolled into thin (2mm) strip, coated and stacked into a laminated core. High performance transformer cores use a 3%Si steel in which the microstructural 'grains' are aligned along the strip in the rolling direction. This alignment results in a 30% increased magnetic flux density along the strip. A careful balance of alloying additions also governs electrical/magnetic properties. Increased silicon inhibits eddy current losses and reduces hysteresis loss. However, high silicon can also embrittle the steel impairing workability. Carbide, sulphide, oxide or nitride precipitates within steel further increase hysteresis losses and reduce magnetic permeability [i.e. the ability to retain a magnetic field]. Hence carbon levels in transformer steels are kept to below 0.0005%. Magnetic properties are also dependent on heat treatment, with increased grain size leading to reduced hysteresis loss. Conversely, incorrect heat treatment and mechanical damage can impair magnetic properties and increase noise due to magnetostriction. Manufacturing control is a critical issue in the production of these lower loss transformer steels.

Amorphous Transformer Steels

Generation of amorphous, rather than crystalline metallic, structures further reduces energy losses. Processing is however complex and involves very rapid cooling of molten metal (at about 1 million degrees per second.) to produce a metallic glass. Higher cost [twice that of normal steels] and lower mechanical properties have tended to restrict their application. However, high cost 'exotic materials' can be justified when balanced against environmental improvements. Ease of magnetisation and reduced core losses [of up to 80% compared with traditional transformer materials] has led to amorphous metal transformers being adopted in developing nations such as China and India [ref.26]. It is projected that China and India could save 25TWh of electricity and eliminate 6-8GW of generating equipment, thereby saving 20-30million tons of CO_2 if this technology were fully utilised.

Insulators and Coolants

The long strings of insulator discs commonly seen on high voltage pylons were traditionally made from a range of porcelain materials. Ceramic insulators were then introduced, followed more recently by lightweight glass-fibre reinforced polymer (GFRP) composites, which are coated with silcone rubber for added weatherproofing and to inhibit tracking. Insulation failure by tracking can occur not only on the outer surface but also between laminations in composite structures. Care therefore needs to be taken during composite manufacture to eliminate any porosity or delamination.

High power transformers require both insulation and cooling. Whilst lower power transformers can be air-cooled more powerful transformers require cooling media to protect and extend insulation life and help reduce corona discharges. Highly refined sustainable, non-flammable, non-toxic mineral oils are being

developed for both insulation and heat dissipation. 'Dry' transformers are often cooled and insulated by nitrogen or hexafluoride (SF6) gas, which is enclosed in a sealed transformer casing. The same gas is used in high voltage switching and poses health and safety issues.

Step Change Technologies

Superconducting Transformers:

An ideal 'no loss' transformer would be 100% efficient. Experimental High Temperature Superconducting (HTS) transformers have been reported [ref.27] with efficiencies of 99.85%. Fuller details on developments in HTS are given in the following section on Electrical Storage.

Health & Safety

Electrical transmission and distribution systems contain a number of features that present environmental challenges. For example:

- The arc-suppressant suphur hexafluoride (SF_6), used in high voltage breakers, is a powerful greenhouse gas. Superior but more environmentally friendly alternatives are sought.
- Hexavalent chromium, used in protective coatings to extend the lifetimes of electrical equipment, is recognised as a human carcinogen if inhaled. Alternative protective coatings are being developed for electrical steels to reduce power loss and noise.

There are also Health & Safety issues associated with the operation and recycling of several new battery systems. These are covered more fully later.

Priorities for Materials R&D

Despite the wide diversity of material needs across the transmission and distribution network, several high priority materials R&D themes can be identified. They include:

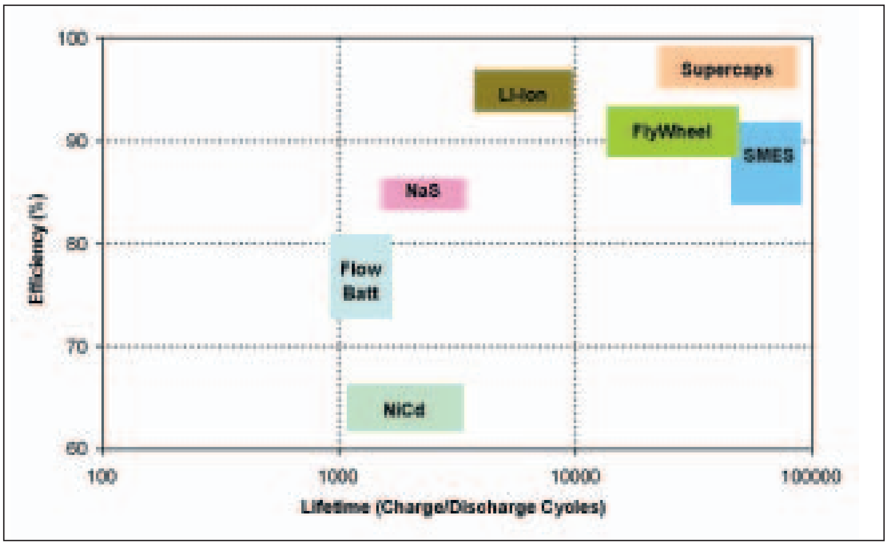
- Developing better lifetime prediction tools for current / future materials and components
- Research into materials technologies to support the application of wide-band gap semiconductors [such as silicon carbide (SiC)] for high power electronic devices
- Developments that enable higher temperature conductors and cabling to be introduced into the transmission and distribution networks
- Development of superior electrical insulation (including nanomaterials) and new methodologies for ultra high voltage and microgrid applications. The need is for higher voltage and temperature capability, longer, more predictable lifetimes and greater affordability.
- Development of amorphous steels for incorporation into lower-loss transformers
- Materials developments on fault current limiters for use in the transmission and distribution. This includes developments in 'high temperature' superconducting fault current limiters [see section 4]
- Research to allow penetration of affordable energy storage materials into the electricity grid network [see also section 4]
- Improved eco-designs leading to reduced use of environmentally damaging materials such as the dielectric arc-suppressant sulphur hexafluoride (SF6) greenhouse gas.

4.0 UK Electrical storage

Instead of feeding power back into the network, excess energy could be stored locally and used to 'top up' distributed power when the sustainable energy source is not operating. The options and materials implications for such energy storage are discussed.

As ever more people use mobile phones and laptop computers and seek more environmentally-friendly forms of transport [such as hybrid/electric cars] then the need for reliable, high power, portable energy systems becomes critical. This is a further high priority area for materials development.

Fig.1. Comparison of lifetimes & efficiencies of different storage technologies [22]



Electrical Storage Methods

Several re-usable energy storage methods are available with different characteristics:

1. **Electrochemical batteries** [including rechargeable or storage batteries] - These are the conventional, relatively low power, batteries used in domestic portable equipment. More powerful rechargeable versions are being developed
2. **Fuel Cells -** As the name implies they generate electrical power from an external fuel supply (often hydrogen). Unlike conventional electrochemical batteries (1. above) they do not rely on an internal energy source and can therefore run almost continuously as long as the flow of fuel is maintained. A more generic term for such cells is 'flow batteries'.
3. **Supercapacitors** - [used for storing an electrical charge]
4. **Superconducting magnets -** [that store electrical power in a (reversible) magnetic field]

Current re-usable energy storage systems have a number of deficiencies:

- They fail to store a substantial amount of energy cost-effectively
- Recovery efficiency is low
- Storage systems are bulky

Lead acid battery storage has been used up to 20MW in Puerto Rico, and in other smaller systems in the USA and Germany. Another possible future approach uses flow batteries, in which energised electrolyte can be pumped away to allow charging to continue with fresh material. These can approach 80% efficiency, but presently have safety problems and high costs.

A comparison of the efficiencies and lifetimes of different storage technologies is given in Fig.1. [22] The high storage efficiency and extended lifetimes of supercapacitors and Superconducting Magnetic Energy Storage (SMES) is clear. These technologies are being developed to 'demonstrator' status to stimulate industrial exploitation [see later].

Supercaps & SMES are at the 'heavy engineering' end of power storage. Most people are more familiar with lead-acid car batteries and the secondary electrochemical batteries used in a wide range of portable domestic appliances. These low power devices are comparable in energy with the much smaller nickel-cadmium (NiCd) batteries [Fig.1]. New chemistries have however been developed which enable these batteries to extend at least into the intermediate size range of automotive vehicles:

Electrochemical Batteries

Small-scale energy storage of a few Watt-hours to some hundred Watt-hours, as used in mobile telephone and portable computer applications require rechargeable electrochemical secondary batteries. Battery technologies are advancing rapidly. The present decade has seen an order of magnitude improvement in energy density.

Battery chemistries based on lithium offer most promise [ref.6].

4.0 UK Electrical storage

'Plug in' hybrid cars will use clean electricity from the mains for daily commuting (up to 60 miles) with a small internal combustion engine as a range extender. Future rechargeable energy storage systems could use a battery for fairly long-term storage and a capacitor to address regenerative braking needs. Hybrid propulsion is likely to 'take off' in the near future such that most vehicles will have hybrid propulsion by 2012. This 'market driver' will lead to extensive development of small-to-medium size batteries and supercapacitors for the automotive sector. Li-ion batteries are a favoured power source for such hybrids:

Lithium-Ion Batteries

Since 1990, rechargeable lithium-ion (Li-ion) batteries have doubled their energy density, the latest, most advanced design being the lithium polymer cell. The charging / discharging characteristics of batteries vary greatly. Unlike nickel-cadmium (Ni-Cd) batteries lithium batteries should be charged early (before full discharge) and often. Li-ion batteries are not as durable as nickel metal hydride or nickel cadmium designs; they are more expensive and prone to thermal runaway. Safety management features are incorporated into Li-ion batteries to control charging and discharging and to protect against accidental damage. Contaminants in the cells can however sometimes circumvent these devices. Because of such difficulties, millions of Li-ion batteries were recalled during 2006 and 2007. New chemistries that avoid such controls would be beneficial. Improvements in power output and battery control have so far come mainly from advances in engineering but these are less readily available. Further advances in energy and power density will come from research on new materials:

The anode of a conventional Li-ion cell is graphite, the cathode is a metal oxide (typically $LiCoO_2$) and the electrolyte is a lithium salt in an organic solvent. Alloy anodes based on silicon and tin are replacing graphite in small cells for consumer electronics. Potentially they can deliver a seven-fold increase in anode capacity over graphite. Replacing $LiCoO_2$ with an oxygen electrode could deliver a five to ten-fold increase in cathode storage. By 2010-15 energy densities of 500 Watt-hours/kg may be possible

Lithium Batteries - Materials R&D

High power batteries are likely to face competition in the next 10-15 years from supercapacitors, which increasingly exhibit good long-term energy storage capability. Another competitor is the small-scale fuel cell. [Fig.2]

A typical modern car battery stores some 40 Watt-hours/kg of power, though more advanced technologies offer values in the low hundreds. In contrast, current fuels (e.g. petrol/diesel) deliver around 13,000 Watt-hours/kg of power. Considerable improvements are therefore needed in battery technology before batteries can be considered as anything more than a complementary to the main automotive propulsion power.

Battery Production

The British Battery Manufacturer's Association gives the value of the UK market in 2001 as £675M, of which 89% was for the "big five alkaline types", with 69% of the market from standard AA (LR6 type).

Low temperature high rate applications constitute an important niche market. Commercially the $LiFeS_2$ battery is marketed for flash

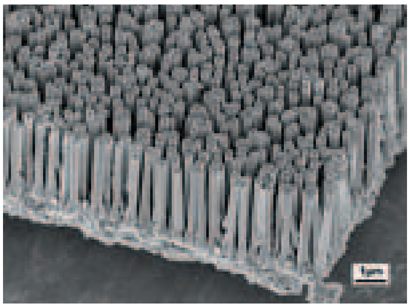


Fig.2. A forest of copper rods ~100nm in diameter providing a large surface area for high capacity battery electrodes [ref.9]

photography but is limited to AA size. Worldwide manufacturing capability of batteries to support the high-volume consumer market already exists in Japan & Korea with China rapidly catching up. UK & EU are niche producers of specialist lithium-ion cells such as long life $LiMnO_2$, $LiSO_2$ & $LiSOCl_2$ and which are used predominantly for low temperature and long shelf life applications in both medium and high rate applications. Currently the cost of these novel batteries is disproportionately high relative to standard alkaline systems.

Molten salt or thermal batteries are a class of high temperature cell that uses molten salts as an electrolyte. They are used for high power density applications and typically need to be operated between 400-700˚C. The Zebra battery operates at 250˚C and uses molten chloroaluminate ($NaAlCl_4$) [m.pt. ~160˚C] as the electrolyte. The anode is nickel and the cathode is molten sodium. The Zebra (Zeolite Battery Research Africa) or technically the $Na\text{-}NiCL_2$ battery is used mainly in heavy military land transport. The battery delivers 150W/kg power. Typical battery lifetimes are over 1500 cycles over a 5-year period with multi-cell packs demonstrating 3,000 cycles over 8 years. Vehicles powered by Zebra batteries have travelled more than 2M Km.

When not in use Zebra batteries are normally left under charge so that they are ready for immediate use when needed. If they are shut down [by allowing to cool], reheating can take up to 2 days before they are at full charge at about 300˚C operating temperature.

Electrochemical batteries are likely to undergo an order of magnitude-plus improvement between 2000-20. From 2012, small-scale fuel cells will become a serious contender to batteries in selected areas. The drive for portable power, particularly in communications, will drive a growing worldwide battery market. New demands from hybrid/electric vehicles will also create opportunities.

Raw Material Security of Supply Issues

There are numerous commercial suppliers of common lithium battery materials such as carbons, $LiCoO_2$, binder, electrolyte etc. but most are not UK based. This is also the case for conventional electrochemical battery manufacturers. Increasing reliance on East Asia, where key suppliers are focussing their business, could cause future supply problems. Soon many 'household name battery suppliers' such as Duracell, Varta, Panasonic & others will all be based in, and supplied from, China, resulting in no UK or EU supplier.

Supply of cobalt raw material used in lithium batteries is of concern because it is available in only a few politically unstable geographical regions. Research is in hand to produce low-cobalt battery variants [as outlined above].

Characterisation & NDE of Batteries: Recycling - Batteries

Significant issues still need to be addressed before batteries will become accepted as an environmentally friendly form of 'portable power'. Mature technologies such as lead acid batteries have well-established recycling systems in place but newer technology recycling procedures are less well developed.

New EU regulations seek to make the battery supplier responsible for recycling. These proposals are currently being studied by DEFRA. A registered and audited recycling programme is likely to be put in place. Industry has dramatically reduced heavy metal contents in batteries but anticipates that supplier recycling/recovery targets will be set in future for batteries. This is in addition to existing WEE regulations, which require portable powered equipment to be designed for easy removal of battery power sources. Currently 700 tonnes of batteries are collected each year. By 2008 the likely target is likely to be 7,000 tonnes. Scandinavian countries already operate local household collection services

Disposal of heavy metals such as cadmium in nickel-cadmium (NiCd) batteries can cause significant pollution in landfill or if incinerated. Part of the price of a NiCd battery in the US includes a fee for proper disposal at the end of its useful life. EU Restrictions of Hazardous Substances (RoHS) banned use of cadmium in electrical and electronic equipment after July 2006 but NiCd batteries were not included in that restriction.

Flow Batteries

There is a wide range of potential fuels that can be passed over active electrodes to generate electricity. Hydrogen-fuelled fuel cells are a well-known example. There is however a wide range of other gaseous and liquid fuels that can be used. Many of these fuels release environmentally damaging materials into the atmosphere [such as polysulphide bromide, vanadium or zinc bromide]. Bromine is known to be damaging to stratospheric ozone. Recycling/disposing of such materials is difficult but the environmental advantages of fuel cells for 'green transport' justify further development.
Increasing wind and other 'green' generators will create a need for large [grid sized] and 'lower large' [distribution sized] storage, resulting in more pumped storage [see later] and effective flow battery systems from 2012.

Batteries - Modelling

Limited capabilities currently exist to model ionic and electronic transfer mechanisms in cell electrodes. There is also need to use performance data to predict useful battery life more accurately under a range of different load profiles.

Small-Scale Fuel Cells

Small-scale fuel cells are a likely competitor to conventional battery power. Direct methanol micro fuel cells have been developed to overcome recharging problems associated with batteries but there are safety concerns associated with these devices. The complex materials issues associated with fuel cells are covered in detail in an associated

4.0 UK Electrical storage

report [ref.10]. Many believe that small fuel cells will replace batteries for relatively low power applications (such as mobile phones; computers; personal electronics; power tools) in the next ten to fifteen years. Market penetration could be in the millions for such fuel cell devices within a decade.

There are currently no satisfactory wholly rechargeable systems for vehicle propulsion, though the best option at present is probably the Li-ion system.

Another alternative is high temperature vehicle batteries such as the Sodium Sulphur (Zebra) system which offers ~5 times the capacity of lead acid batteries.
The most likely fuel for fuel cells is hydrogen in either in high-pressure gas or liquefied form. A supply infrastructure would be required similar to that which currently exists for petrol and diesel distribution. Materials issues are 'non-electrical' and are outlined later.

Supercapicitors

Supercapacitor devices complement batteries, providing sudden bursts of power for relatively short periods. A typical car may have an average power requirement of 30 kW but peak power of 60 kW (during acceleration or hill climbing). Provision of 60 kW battery power would be expensive and may pose weight problems. If supercapacitors are added into the power train, battery power requirement can be effectively halved. For this reason, supercapacitors are likely to be an essential component of future "green" automotive power train systems. They will also play a role in providing power quality from intermittent and variable renewable systems (such as 'wind farms'.) Development of supercapicitors is therefore essential for a 'low carbon' energy future.

Supercapacitors will see applications in consumer electrical goods when brief recharge/discharge properties are required [for example in electrical screwdrivers, hair dryers etc.] Niche markets include military applications.

Supercapacitor Production

Current global production capacity for supercapacitors is not sufficient to supply future demand. This provides a strong market opportunity for UK to take a dominant position. Supercapacitors are already manufactured by a number of companies, mainly in Japan & USA and many of the process conditions are well established. There is however no current UK manufacturing capability.

A COST programme is seeking to set up a European manufacturing capability probably based in Germany, initially using Russian technology for large plate supercapacitors.

Conventional aqueous systems have significant environmental benefits compared to lead and lithium based batteries but the environmental advantages of non-aqueous supercapacitors are less obvious. At present superconductors are based on commercially available and relatively crude carbon. The UK is well positioned to offer more precisely tailored carbon properties, from which a worldwide supercapacitor capability might be developed. Supercapacitors: Characterisation, Non-Destructive Evaluation (NDE), Assessment, Protective Systems and Modelling.

Recycling Supercapacitors

Double layer supercapacitors contain no environmentally sensitive heavy/precious metals. They do however contain ionic liquids that often contain harmful chlorine and fluorine functionalities. Amounts are small and device lifetimes are long so that leak-proof containers should prevent any release. There is however need to address the ultimate disposal of the organic/ionic liquid electrolytes.

Supercapacitor R&D

Part of the EPSRC Supergen programme is seeking to build novel devices with significantly higher storage capacity. These high-energy devices rely on small amounts of relatively expensive ionic liquids. To exploit the large global market it is desirable that the UK establishes a manufacturing capability.

The COST 542 EU project is dedicated to the commercialisation of current supercapacitor devices. A system has been installed in a diesel locomotive that generates 1500A at 60V. The 'supercaps' [Fig.3] replace a much larger conventional battery system. COST 542 is also developing higher storage density devices. Conventional aqueous electrolyte systems operate at around 0.7V with a maximum power of 22kW/kg and a storage density of 3.6Wh/kg. New asymmetric carbon-MnO_2 systems have demonstrated a maximum power output of 123kW/kg with a power density of 12.6Wh/kg although densities of up to 28.6Wh/kg have been demonstrated. Higher densities will be achieved. Non-aqueous electrolyte systems offer higher power but with greater environmental impact [See above]. These devices have the benefit of operating at high voltage and high current with rapid charge/discharge capabilities but are strongly dependent on the availability of 'controlled structure' carbon electrodes.
Current developments involve controlling the interaction between the electrolyte and the electrode surfaces via controlled micro/meso-porosity systems and nanofibre composite systems. The nanotechnology is similar to that outlined for batteries [see above]. Work is also ongoing to moderate the way in which 'supercaps' discharge so that behaviour is more similar to batteries. (Double Carbon Battery Company)

Superconducting Magnetic Energy Storage (SMES)

SMES offer improved performance and efficiency (98-99%) compared with the 90% of other utility devices such as fuel cells. SMES store energy in the magnetic field of a DC current that flows in a superconductor wire / tape. Energy losses are negligible, making it possible to inject and extract current very quickly. Because the major parts in an SMES are static wear is minimal and reliability is high. One major constraint is the need to operate at cryogenic temperatures. Power used in the refrigeration process must also be taken into account in any rigorous energy balance. In Fig.4 an illustration of a schematic design of an SMES [24].

A range of modelling capabilities are needed, together with structural and electronic materials developments to facilitate the introduction facilitate the introduction of superconducting materials:

- Superconducting behaviour depends critically on the cryogenic operating conditions and on the manufacturing route used to make the multi-filamentary wires. The original superconducting material is produced in powder form but is consolidated, extruded and produced as a fine filamentary wire. Many hundreds / thousands of filaments are then drawn into the final superconducting wire. Alternative forms include deposition as tape. Materials modelling and characterisation at all stages in the production and operation is needed to optimise behaviour.
- The superconducting wire/tape has to be held in a structure that must withstand high Lorentz forces, together with electro/mechanical and thermal loads. Materials must be developed to withstand these structural demands.
- The electrical properties of high temperature superconducting wires need to be optimised for high power transmission. Modelling capabilities again simulate operation conditions.
- Superconducting wires carry high currents and voltages. The supporting structures need to be protected against electrical discharge via insulation and isolation. This type of protective control also needs to be modelled.

Fig.3. Supercap Field Trial Used for starting 1000shp diesel locomotive with Supercap provides 1500A at 60V
[Courtesy of MASTCarbon Technology Ltd]

Applications for SMES

SMES offer commercial and power management benefits that include:

- Maintaining quality power, stability and reliability across the transmission and distribution networks.
- Avoiding outages and use of environmentally-friendly materials
- Greater control, flexibility, response & convenience in energy storage and delivery
- Enhancing asset utilisation and deferring upgrades by including storage capability at the substation level
- Facilitating continuous electricity supply by storing excess capacity from intermittent renewable energy generation sources.

Fig. 4: A Schematic design of SMES [24]

Use of superconductivity in power transmission will also provide the following technical benefits:

* Reduced losses - from about 10% to negligible losses for DC systems and very small losses for AC systems
* Up to 5 times more power capacity for the same cable size

Micro-SMES devices [1-15MW] are commercially available using NbTi Low Temperature Superconductors (LTS) (4K). The materials are still expensive and need expensive liquid helium cooling. In 2006 USA, Japanese & EU began introducing High Temperatures Superconductors (HTS) (20-70K) into demonstrator programmes. These devices require less expensive cryogenic cooling methods.

4.0 UK Electrical storage

As the cost of superconducting materials fall and the cost of energy increases, then SMES will become more cost-effective allowing increased numbers of power utilities to be integrated into its transmission and distribution systems

Superconducting Materials:

Commercial high temperature superconducting materials currently include:

1. 1st Generation (1G) BSCCO 2223 [Bismuth-Strontium-Calcium-Copper-Oxide]
2. 1G (BSCCO 2212) [Bi-Sr-Ca-Cu-O - with the numbering indicating the number of compounds]
3. 2nd Generation (2G) YBCO [Yttrium-Barium-Copper-Oxide]
4. MgB_2 [Magnesium diboride]

Most materials are still expensive [400 per kilo-Amp-metre (KA-m) for HTS vs. £10 per KA-m for LTS. An expected reduction in production cost for 2G superconductors and a general increase in energy and gas costs will accelerate commercial use of HTS.

Trends in Power Utilities Use of Superconducting Materials

Use of superconducting materials eliminates energy losses to such an extent that high voltage transmission would no longer be necessary. Hence introduction of superconductors would revolutionise the transmission and distribution network allowing relatively low voltage energy transfer across the system. Fig.5 illustrates the relatively complex engineering required for future HTS cabling. Superconducting cables are currently in use in the USA & Japan but not in the UK.

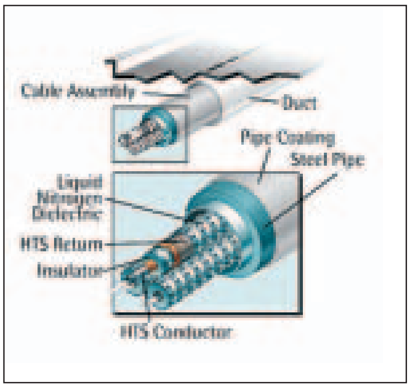


Fig.5. Construction of a cryogenic dielectric HTS cable [ref.11]

Use of lower voltage transmission would also reduce the size of transformer substation facilities. Japan & USA are working on programmes for an 'all superconducting' substation that would be more efficient than current equipment and offer:

- 25-30% reduction in size
- Less maintenance
- Up to 3-5 times more power capacity for the same equipment 'footprint'
- Intrinsic fault current limiting capabilities

In order to achieve commercial levels of storage it is necessary to wind hundreds of miles of fine filamentary wires into superconducting magnetic energy storage (SMES) devices. This means that SMES facilities are large and require advanced engineering in the in the exploitation of superconducting materials. In the UK there are many companies that have successfully exploited lower temperature superconducting materials (LTS) to manufacture state of the art scientific and medical instruments. Fig.6 illustrates the world leading high field (950MHz NMR) superconducting magnet, which is the size of a double-decker bus and is installed at Oxford University.

Fig.6. High Field Superconducting Magnet installed at Oxford University for NMR experiments. *[Courtesy Oxford Instruments]*

There is need to develop superconducting power cables and to produce commercial prototypes of superconducting fault current limiters. Increased worldwide use of energy places severe strains on existing electrical infrastructures. This results in more frequent 'blackouts ('outages'). Even millisecond outages can cause computer 'crashes' with multi-million pound commercial consequences. The introduction of 'instantaneously acting' fault current limiters into the network can eliminate these outages.

A superconducting fault current limiter [Fig.7] is essentially a long length of superconducting wire (coil) contained within a refrigerated container. The cooled wire is coupled to grid equipment. When a fault occurs, for example by a lightning strike, the resulting high current causes the superconductor to 'saturate' and it immediately returns to its more normal resistive state. Because this behaviour is an intrinsic characteristic of a superconductor there is no need for complex supporting relays.

Commercial use of fault current limiters must take into account both performance and costing issues. Magnesium diboride (MgB_2) is a useful superconducting despite it's more limited 'high temperature' capabilities. It has a critical temperature of 40K but is a cheap and easily obtainable metallic compound that can be readily converted into wire. This material is now being exploited as fault current limiters in order to protect the grid. Wider applications are envisaged. USA & Japan are developing more expensive oxide ceramics that operate at less stringent cryogenic temperatures. It is expected that these new second generation of high temperature superconductors will revolutionise the power generation, transmission and distribution.

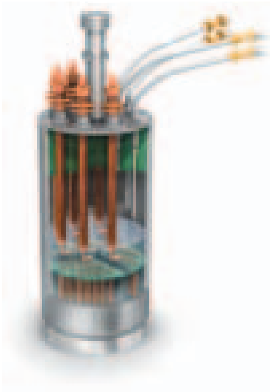


Fig.7. A Fault Current Limiter Design using BSCCO material [ref.12]

Fig.8 illustrates a fault current limiter that uses BSCCO material for HTS components and is capable of operating up to 110KV [ref.22]

The UK has considerable expertise and skills in superconductivity and associated cryogenic engineering at universities, government facilities and major UK companies.

Materials R&D for Electrical Storage

- Lower cost, longer life, high rate lithium-ion batteries with low cobalt additions and order of magnitude increased power output for 'portable power'.
- Introduction of a recycling and disposal infrastructure
- Nanostructured high capacity battery and supercapacitor electrodes.
- Demonstration of high storage capacitors, high density asymmetric carbons and innovative non/aqueous electrolytes via European collaborative programmes.
- New electrode/electrolyte chemistries for fuel cell technology [see related report]
- The potential benefits of superconducting materials for 'zero loss' energy transmission, distribution and energy storage are so great that major emphasis should be given to developing cost-effective manufacturing technology to allow 1st & 2nd generation HTS materials to be used initially in demonstrator cabling, fault current limiters and energy storage, followed by full commercial exploitation.
- Continued long-term materials (20years+) with the aim of achieving ambient temperature superconducting materials.


LNG

5.0 Alternative energy storage methods

There are a number of alternative reusable energy storage methods in addition to electrical storage. These include storing energy as fuel or using excess electrical power to generate work that can subsequently be converted back into electricity.

‘Regenerative’ power systems include:

- Pumping liquid from a low to a higher level [which later drives a water turbine]
- Compressing a gas [which is later released to drive a turbine]
- Driving a flywheel [as in regenerative braking]

One-off Fuel Storage systems will require:

- Lightweight [composite] pressure vessels for more cost-effective transportation
- Safe hydrogen storage systems for renewable sources
- Materials with high toughness capable of operating at low temperatures.
- High integrity containment vessels for the long-term storage of hydrogen under pressure. There is a need to establish the fatigue life of steels with small defects in hydrogen environments.
- Development of alternatives to 9% Ni steels for more economic storage of liquid nitrogen gas (LNG) or liquid hydrogen.

Hydrogen

The subject of hydrogen transportation and storage is dealt with comprehensively in **Report 4** of this series of MatUK reports (ref 15). Reference should be made to this for full details of the current status of R&D, future requirements and recommendations. This brief section is included here for completeness and does not cover the key recommendations, for which the reader should consult to reference 15.

Hydrogen transportation

Hydrogen can be transported in gaseous or liquid form via land or sea. Land transport can use road tankers but the ‘carbon footprint’ can be large. Below ground pipeline transfer is a relatively secure and environmentally attractive option but engineering costs are high and construction times can be protracted. Several existing hydrogen pipelines exist, although most are of relatively short length. The longest network is 834km of pipeline in Belgium, France & the Netherlands. These pipelines are usually manufactured from carbon steel. Road transportation uses pressure vessels made from carbon or low alloy steels. For long distance transportation, compressed hydrogen in steel pressure vessels is not considered an economic option due to the mass of the pressure vessel. Composite structures are however a future option.

Materials R&D for Transporting Hydrogen

Hydrogen gas or supercooled liquid present particular challengers to the materials engineer. Hydrogen can reduce the fatigue behaviour in carbon steels. Understanding this behaviour is critical for the integrity of hydrogen transmission lines. Hydrogen compressor station designs will also need to be modified from existing natural gas facilities because the energy per unit volume of hydrogen is approximately one third that of natural gas. It is not possible to transmit hydrogen gas through polymeric pipelines because diffusion of hydrogen through the polymer is too high. Instead hydrogen might be incorporated into existing natural gas mixtures at levels up to 15-20% without risk of damage to the pipeline [13].

Gas mixtures such as hydrogen, carbon dioxide and methane could be carried long distances in existing pipework and then distributed independently using gas separation membranes. Such combined networks require improvements in current gas membrane technology. Special attention needs to be given to gas mixtures containing CO and CO_2 (such as Syngas) as the CO can cause stress corrosion cracking and other corrosion problems, particularly with CO_2 in the presence of moisture. Coatings and specific steel types are required that are resistant to attack by these gases.

Transportation of liquid hydrogen by sea has been investigated in Canada to support their use of hydroelectric power for manufacturing large quantities of hydrogen for export [14]. Liquid hydrogen presents a number of difficulties in transportation. Temperatures are much lower than for LNG transport [-253°C compared to -163°C] and materials used in manufacturing containment systems must therefore have better low temperature characteristics. A further challenge is the development of insulation systems that will reduce ‘boil-off’ rate of hydrogen during transportation to levels that allow more economic transportation. Such factors are less critical if the hydrogen is transported as a gas.

Liquid hydrogen has a lower specific density than water, which presents problems in hydrogen tanker design. Novel twin-hulled tankers would need to avoid the large quantities of ballast used in single hull designs. Alternative methods of hydrogen transportation such as methanol or ammonia transportation are also at an early stage of material development. At present there is a very limited infrastructure worldwide for hydrogen distribution and storage.

5.0 Alternative energy storage methods

Summary of Materials R&D for Hydrogen Transportation

- Development of high toughness/low temperature steels and modelling methods to predict long-term behaviour of such pipework when transporting liquid or gaseous hydrogen. Assessment of sub-zero fatigue behaviour in the presence of small-scale defects.
- Development of improved steels and insulating coatings to withstand temperatures below -250˚C for transportation of liquid hydrogen
- New steels and coatings technology to provide corrosion resistance in combined hydrogen, carbon dioxide and methane gas mixtures, particularly if contaminated with moisture.
- Gas membrane technology for subsequent separation of gas mixtures.
- The design/engineering implications of using composite materials for high integrity cost-effective transport and storage of hydrogen gas under pressure.

Hydrogen Storage

Technologies:

The possible introduction of a hydrogen fuel infrastructure (in conjunction with fuel cells) to complement or replace petrol / diesel driven transport, will require extensive hydrogen storage systems, both for the supply sector and for individual vehicles. High-pressure hydrogen storage has been demonstrated, but lacks customer appeal for safety reasons. Safe and efficient storage of hydrogen is critical if fuel cell vehicles are to be economically viable within 10-15 years. Many high-capacity candidates, such as complex chemical hydrides and hydrogen adsorbents, are under investigation. Further details of some of the materials requirements can be found in an associated report [ref.15]. Novel hydrogen storage techniques, using materials ranging from exotically nano-structured carbon to rare earth element absorbers, continue to offer tantalising prospects, but are still at the basic research level.

Hydrogen Storage - Standards

Standards need to be developed for thermo-chemical and life-cycle characterisation of hydrogen storage systems for objective comparison and commercialisation of products. Life-cycle analysis is also essential for reversible hydrogen storage systems. Such systems would need to maintain 80% [say] of their original capacity during their lifetime of 1,000 cycles [say]. Considerable work is needed to develop transparent safe systems and operating procedures for use with hydrogen.

Summary of Materials R&D for Hydrogen Storage

The recommendations for R&D priorities for hydrogen storage are given in Volume 4 of this series of MatUK reports (ref 15) and reference should be made to it for the full details.

6.0 UK Oil & Gas perspective

This section concentrates on the transportation, distribution and storage of oil and gas and their associated materials challenges. It starts with an overall perspective of the oil and gas markets in the UK.

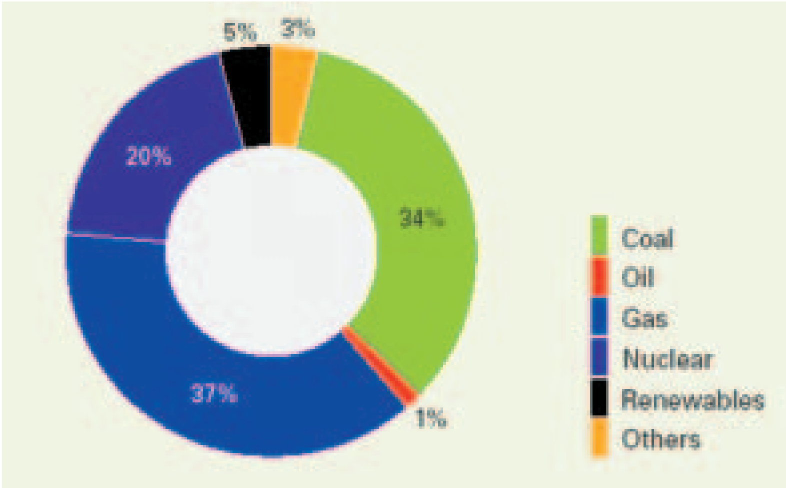


Fig.8. Current % UK Energy Mix [Source: DTI 2006]

Current UK Energy Mix:

Fig.8 demonstrates that the UK has a diverse spread of different electricity generating capacity, thereby reducing dependency on any one fuel type and helping to maintain security of supply. However over the next two decades this diversity will be eroded:

Future UK Energy Mix:

Without changes to current market mechanisms, the percentage of UK electricity produced from gas-fired power stations is likely to rise from the present 37% to around 57% by 2020 [Fig.9]. UK fuel diversity would be impaired if well over half the UK electricity came from gas.

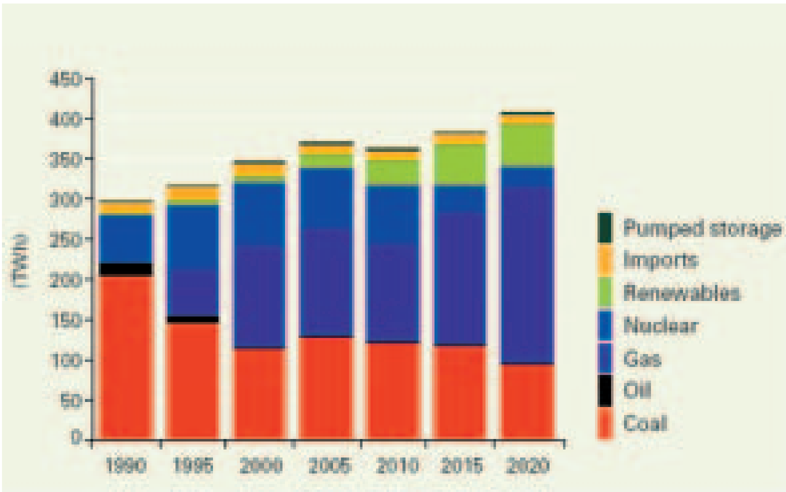


Fig.9. UK Electricity Generating Fuels (TerraWatt hours) [Source: DTI 2006]

Oil:

Future Global Oil Mix:

The dominant global fuel for the next 25 years will be oil, with OPEC suppliers increasingly taking a larger proportion of that total [Fig.10]. About half of global production is exported. It is predicted [ref.17] that inter-regional oil trade will increase from 31M barrels/day in 2002 to 43M barrels/day in 2030.

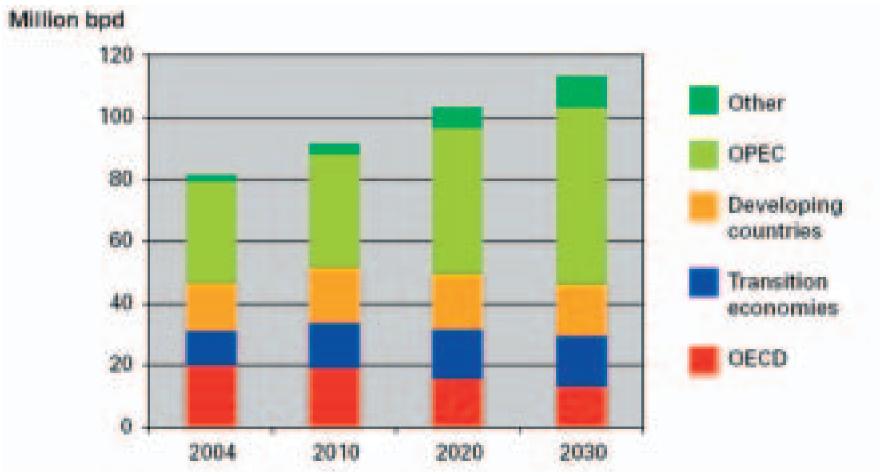


Fig.10. Global Sources of Oil Production [DTI Energy Review July 2006] [bpd = barrels per day]

6.0 UK Oil & Gas perspective

Global Oil & Gas Reserves:

Global oil and gas reserves are heavily concentrated in Russia, Central Asia, the Middle East and North Africa [Fig.11]. The Middle East will remain the largest oil-producing region. OPEC holds 75% of proven oil reserves and its market share is projected to rise from 40% in 2005 to 50% by 2030.

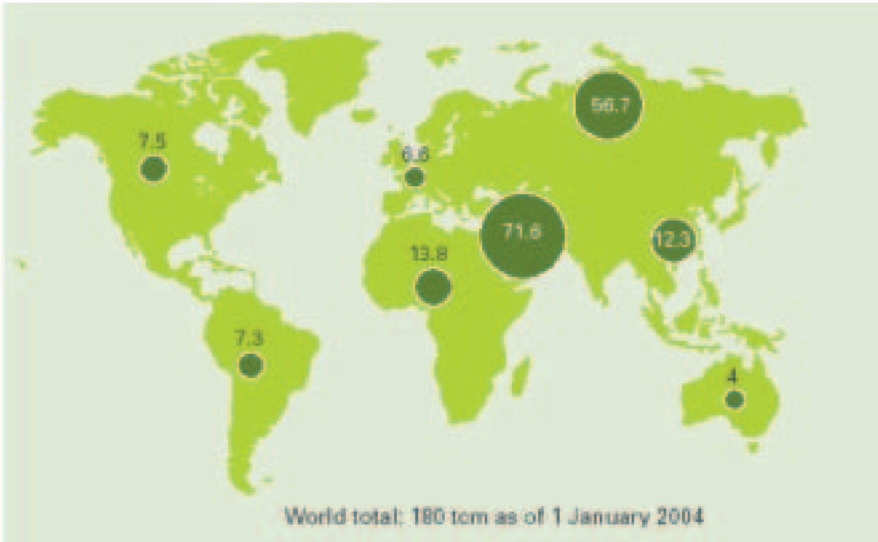


Fig.11. Proven World Reserves of Gas (2004) [Source: Cedigaz 2004]

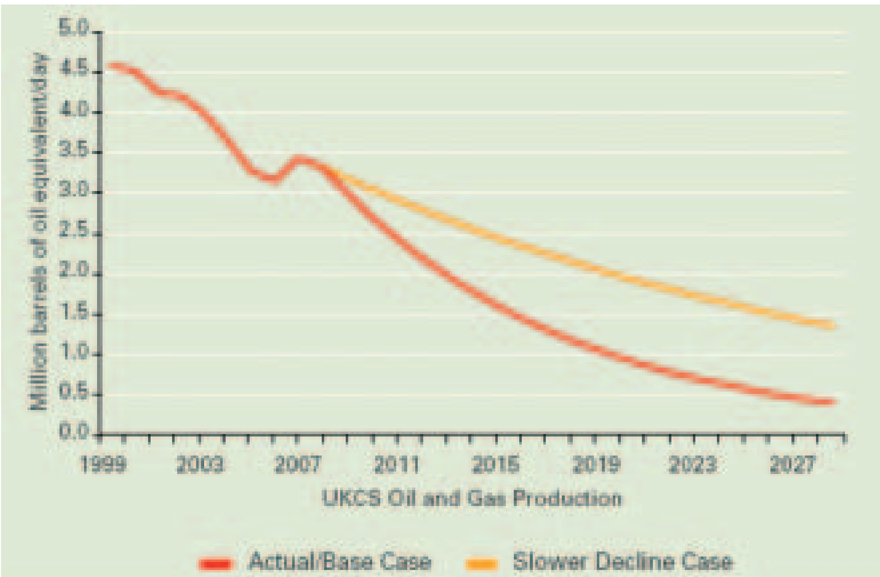


Fig.12. Total UK Continental Shelf (UKCS) Oil & Gas Production Rate [to 2030] [Source: DTI - UK Offshore Operators Association 2006]

Norway will remain a significant medium-term supplier of gas to the UK, along with Algeria and Qatar. Over time, UK imports are likely to increase from Russia, the Caspian and Nigeria.

World gas reserves are mainly concentrated in large reserves in former USSR countries or in the Middle East. Large gas hydrate reserves [estimated to be much larger than conventional gas reserves] exist in northern Russia & Alaska. Approximately 50% of world proven conventional oil reserves are located in the Middle East, which accounts for approximately 25% of world supply today but is expected to increase to around 43% by 2030. Concerns over security of supply will therefore drive the exploitation of more marginal reserves and non-conventional sources of oil such as oil shale / oil sands, sour gas or tight gas. It is estimated that approximately 20% of undiscovered oil reserves outside of the Middle East are likely to be located in deepwater areas and 30% in arctic regions [ref.17].

To maintain world oil supplies, future capital investment will concentrate on exploration, production and refining. Investment in the gas industry will mainly focus on creating an efficient transportation infrastructure to supply worldwide markets.

UK Oil Reserves:

After 40 years, UK Continental Shelf oil and gas production is now declining. If the 9% p/a rate of decline experienced during the last decade continues then the red line (Fig.12) will be followed. However recent investment in new production facilities has enabled more oil and gas to be recovered, thereby slowing the decline to 4% p/a (the orange line Fig.12) and resulting in:

- An extra 1 million barrels of oil equivalent (boe) to be delivered in 2020
- Nearly 7bn boe of extra production to be achieved by 2030
- The UK will however be a net importer of oil by 2010.

Current Status in the Oil Sector

Transportation and storage issues have largely been resolved in the oil sector. Long distance transportation is mainly by tankers with storage in steel tanks. Materials used in these systems are well characterised. Because of the huge volumes of oil transported, weight savings for bulk vessels are not likely to be pursued. Shipping bottlenecks are likely to become more of an issue in future and solutions for easing bottlenecks drive vessel development [ref.17]. Existing assets are ageing so condition monitoring and life extension become increasingly important. A greater focus on safety and environmental impact is likely to influence future designs of infrastructure, perhaps leading to the adoption of tougher steel grades for vessel construction and greater use of double-hulled vessels. A number of fabricators with the expertise to manufacture oil storage facilities exist in the UK although oil tanker construction is now largely dominated by far eastern shipyards. Steel plate used for both is manufactured by Corus although a relatively small proportion of production ends up in this application. UK has considerable oil and gas expertise following years of North Sea oil development.

Materials Development in the Oil Sector

Two areas in the oil industry where materials issues still exist are:

- Transportation of oil from wellheads to the surface at deepwater fields and:
- Transportation of CO_2 for CO_2 - enhanced oil recovery and sequestration schemes.

Flowlines and risers are typically constructed from carbon or low alloy steel. In deepwater and arctic applications, low water temperatures may result in the oil cooling rapidly on leaving the well. As the oil cools, flow rates drop and during halts in production the oil can solidify. Insulation systems are used to minimise freezing but there is scope to develop more advanced insulation systems for use in deepwater applications. At depths of 1500-3000m the total mass of the risers leads to relatively high static stresses, repeated movement can lead to fatigue issues. Materials with improved fatigue resistance are required. Alternatively the risers might be manufactured from lightweight materials such as carbon fibre wrapped polymer systems [17]. Due to conservatism within the industry and problems associated with rectifying in-service failures in deep water, lack of data on long-term performance of new materials can delay introduction of new designs.

Deepwater fields often contain higher levels of sour gas (containing H_2S). Exploitation of such high 'sour gas' fields is now being developed. Traditional carbon steels are susceptible to hydrogen embrittlement and corrosion under such conditions. Use of corrosion resistant alloys could increase in future but their high alloy cost provides scope for clad pipes or development of lower cost steels specifically for sour gas applications.

Carbon dioxide enhanced oil recovery involves injecting CO_2 to increase oil recovery rates. Use of this technique is expected to increase in future as it provides a means for using/storing CO_2 produced in fossil fuel power generation/other industrial processes ['sequestration']. Transportation of CO_2 to the oil field would typically use carbon-steel pipelines. However these steels are susceptible to severe corrosion if moisture is present in the CO_2 gas. Drying stations commonly remove moisture prior to transportation. Opportunities exist for coatings or steels more resistant to CO_2 corrosion in order to minimise or eliminate the need for drying. Once a gas reservoir has been filled, it needs sealing. The long-term integrity of cements and polymers used to seal wells need further characterisation to eliminate possible CO_2 escape. Improved materials are again needed.

6.0 UK Oil & Gas perspective

Gas

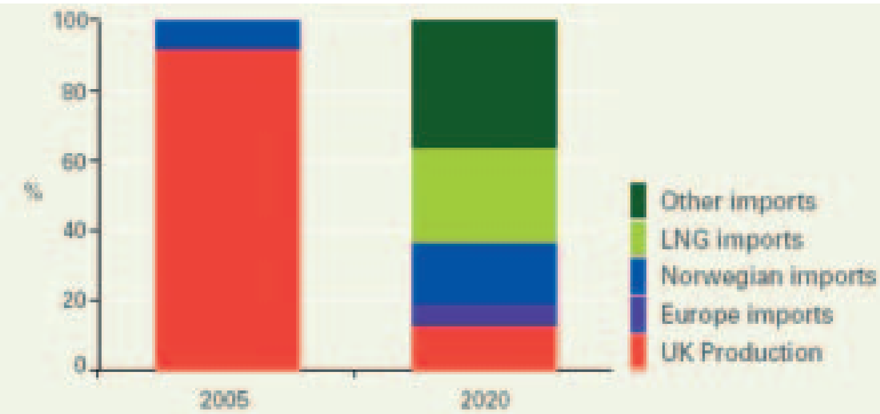
Current Status:

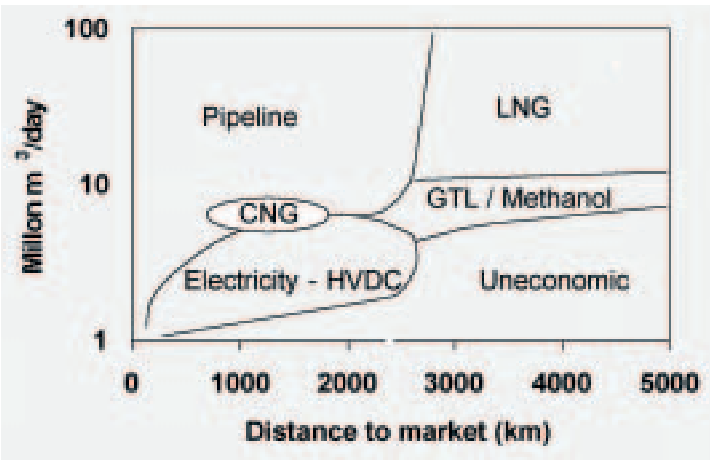
UK gas imports will grow strongly in the next decade. In 2005 95% of UK's natural gas was obtained from the North Sea (Fig.13). By 2020 over 90% of UK gas supplies will be imported.

As North Sea reserves dwindle there will be future reliance on imported gas from Norway, LNG, or Russia via continental Europe. Future supply by 2015 is predicted to be [ref.16]:

- About10% from UK North Sea
- 30% from Norway
- 15% via the Interconnector
- 35% from LNG
- The remaining 10% from new projects

Fig.13. UK Gas Imports 2005 & 2020
[Source: Wood Mackenzie 2004]





Transportation and Storage

Inter-regional gas transportation is expected to triple from 417 bcm (billion cubic metres) in 2002 to 1260 bcm in 2030. Energy costs will remain high because of high-energy usage worldwide, particularly in emerging economies such as China and India. Fig.15 illustrates UK demand and supply capability and the potential sources.

The market for Liquid Natural Gas (LNG) is still developing. UK will expand its LNG import facilities by adding more than 100M cubic metres/day over the next 5 years. £10bn investment is planned for new LNG pipelines and import terminals. These facilities could deliver 100bn cubic metres or more of LNG by 2015 - sufficient to meet future forecasts for gas imports. [ref.16]

A huge investment in gas infrastructure is expected over the next 25 years to meet predicted increases in world gas transmission. Current transmission technologies include:

- Pipelines
- Liquid Natural Gas (LNG)
- Compressed Natural gas (CNG)
- Micro LNG
- Conversion of gas to liquid (GTL) [e.g. gas-to-diesel]

LNG offers the best economics for large-scale transportation over distances >3000km, whereas pipelines offer the best solutions over distances up to 3000km or where sea transportation is not available. CNG and micro-LNG offer solutions for medium-scale transmission over shorter distances Fig.15. [2]. GTL technologies for liquid petrochemical transportation are mature, but other technologies present a range of material challenges.

Fig.15. Areas of applicability for different gas transport technologies

Long-term large-scale underground storage is achieved by injecting gas into suitable rock formations or by using 'spent' oil/gas fields. Short-term storage may use gasometers, for which the engineering and materials are well proven, or pressure may be raised in the transmission network to accommodate extra gas. Liquid Natural Gas (LNG) gas storage at terminals is becoming increasingly important.

Materials Development in the Gas Sector

Pipeline Materials

Increasing demand for gas from both China & India will require construction of several long-distance gas pipelines. Transportation of gas from remote gas fields in Alaska and northern Russia will require pipelines that can operate at low temperatures. Long-distance gas transmission lines require higher strength pipes than the current standard [X70-X100] steels to allow throughput of gas to be increased by ~50% [for the same wall thickness and pipe diameter] [ref.18]. X100 steel grades are currently being developed in order to increase strength [to X120 levels]. Production of steels with the necessary combination of strength and toughness are difficult and microstructures are complex. A better understanding is required. Welding technologies and consumables suitable for seam and girth welding also need to be developed. Demonstration projects would build up experience and test the applicability of design rules for high strength pipelines. Alternative methods for production of high strength pipelines include composite wrapped pipe. Worldwide supplies of carbon fibre are insufficient to support large-scale manufacture of such composite pipes. Little experience exists, particularly regarding the long-term durability of composite materials, compared to conventional welded carbon steel pipe. In large high-pressure Russian pipelines up to 10% of the energy transported is used to power the compressors. More efficient gas turbines (or electric motors) driving efficient compressors would help improve the economics of long-distance pipeline transportation.

High toughness materials are required for low temperature pipeline materials in order to arrest any potential fracture. Future exploitation of gas hydrate deposits in arctic regions will place more onerous demands on low temperature toughness. While a current typical pipeline specification might require impact toughness at -20°C, some arctic specifications could require high impact toughness levels at -40 or -60°C. Since toughness tends to decrease with strength, developing combined high strength/high toughness steels will prove difficult. Similarly CNG pipelines will require high strength (typically X80 or higher) in combination with high toughness at -40°C to cope with high pressures/low temperatures of gas transportation.

UK gas transmission is mainly via medium strength, carbon-steel pipelines. The distribution network operates at significantly lower pressures than transmission lines so that polymer materials are suitable. The UK transmission network is mature. Further development will mainly involve connecting new terminals to the existing grid, plus replacement of ageing assets once current projects have been completed. Condition monitoring and lifetime prediction are critical areas of development for gas transmission.

Materials R&D in Pipeline Materials:

Pipeline materials, whether for oil, gas or hydrogen, require the following developments:

- Design/performance criteria for composite pipes used in high-pressure pipelines
- Condition assessment of current steels for better lifetime estimates
- Development of fatigue resistant riser systems and possibly lightweight risers.
- High strength (X100-X120)/ high toughness pipes for improved efficiency of long-distance onshore gas transmission and oil/gas transmission in cold climates.
- Detailed metallurgical understanding of pipeline steels for better welding procedures and fuller characterisation of fracture response.
- Development of thick wall intermediate strength pipe plate for deep-water pipelines. There is also a need to understand the effect of pressure and prior service history on pipeline integrity and long term degradation in the presence of hydrogen.
- Development of coatings to improve oil flow rates, enhance corrosion resistance and minimise hydrogen embrittlement.
- Development of lower cost cryogenic steels for improved economics & more efficient insulation systems for deepwater pipelines and LNG/liquid hydrogen transportation.

6.0 UK Oil & Gas perspective

Materials for LNG Transportation

LNG supply is predicted to increase significantly by 2030. The International Energy Association (IEA) predicts a fivefold increase in liquefaction capacity, while the associated shipping fleet will increase from approximately 179 to 600 vessels. In Europe the number of re-gasification facilities is predicted to double by 2015 [ref.19]. Several materials used in the construction of LNG facilities have to withstand temperatures as low as -160°C. The standard choice of steel for re-gas facilities contains 9% nickel [although austenitic stainless grades and nickel-alloys can also be used]. Nickel prices are currently very high, increasing the cost of these cryogenic materials considerably. In order to reduce the capital costs of LNG plant, development of lower cost alternatives to 9% nickel steels would be beneficial. Most modern LNG carriers are of 'membrane' design with an Invar inner tank surrounded by insulation, which is supported by the carbon steel ship's hull. Greater transportation efficiency can be achieved using larger vessels with an improved insulation layer.

Materials for CNG Transportation by Ship

CNG transportation depends critically on the availability of lightweight pressure vessels for gas containment. The first demonstration ship built in the 1960's indicated that transportation in steel pressure vessels was uneconomic because of weight penalties. More recent designs involve:

- Polymer lined composite pressure vessels
- Steel lined composite pressure vessels or:
- Composite pipes with either polymer or steel liners.

Most composite materials do not suffer from common corrosive degradation mechanisms. Whilst this has obvious advantages for their long-term structural effectiveness, it poses difficulties for subsequent disposal. Such materials are unlikely to represent a hazard at landfill sites but alternative environmentally friendly disposal methods would be preferable

Over 40% of the cost of a CNG vessel is the cost of manufacturing the storage system. None of these systems has yet been used in a production vessel. There is an urgent need to improve the economics of CNG transportation by reducing manufacturing costs for composite gas containment systems.

UK Corus Tubes Energy manufactures a range of pipes for gas and oil transmission. The steel is manufactured at the Corus UK plate and strip mills or, for certain grades, imported from European steel mills. Turnover of Corus Tubes Energy is ~£230M p/a and the pipe mills are acknowledged as being world class. Several UK businesses manufacture pipeline fittings, while Rolls-Royce manufacture natural gas compressors.

Pumped [Water] Storage Systems

There are currently few options for energy storage on the scale of power-grid demand-curve smoothing other than pumped water storage systems, which require extended 'start-up' times. Effectiveness of such systems depends upon the hydrodynamic efficiency of turbines, pumps and the ability of transmission systems to switch heavy loads without arcing. Most of these requirements are common to other large-scale generation systems, including wind and water-turbines. Materials requirements for these power generators have been addressed in other associated energy documents [ref.20.21]

Fuel Storage Tanks:

Fabrication of pressure vessels has migrated from the UK to countries with lower labour costs. Currently few specialist pressure vessel manufacturers remain in the UK. The optimum choice for many applications is carbon fibre reinforced composite structures. Major areas where the UK is expected to contribute include: -

* Pressure vessels for hydrogen storage and transportation
* Improved liquid natural gas (LNG) transportation and more economic storage
* Development of tankage for large-scale transport of compressed natural gas (CNG)

Future large-scale power storage will offer new market opportunities. Superconducting Magnet Energy Storage systems (SMES's) using high temperature superconducting materials are still at the R&D stage but offer far reaching opportunities for the UK to develop devices able to meet many UK and worldwide future power needs.

7.0 SWOT analysis

SWOT Analysis of UK Transmission, Distribution & Storage Capabilities

Strengths

- UK knowledge base in current materials used in electricity and gas transmission (due to managing ageing asset base)
- Exportable knowledge, i.e. feed-through into international Standards
- Historic knowledge of old assets
- Capability of pipe manufacturing plant
- Only 10 competitors worldwide in the manufacture of electrical steels
- High-tech. product limits new entrants into market
- Limited alternative materials to electrical steels in transformer cores
- World leading skills and expertise in superconducting and cryogenic applications

Weaknesses

- UK knowledge base is largely in the industrial sector, not academic
- UK industry is not driving materials R&D.
- Lack of “new blood” being developed
- Industry not considering full life cycle costs.
- Reliance on imported feedstock in some cases
- Conservative approach to new technologies results in long lead times for their introduction
- No linkage between short, medium and long term R&D strategies
- Government and private funding to support high risk

Opportunities

- Development of high value, specialist, low volume materials.
- Trialling new technology for current UK asset replacement programme and enabling connection of Renewable generation.
- Cheap high strength high toughness steels.
- Material diagnostics/testing.
- Sensing technologies for condition-based maintenance/replacement strategies.
- Low maintenance assets e.g. no painting required
- Trading of CO_2 equivalents/ banning of SF_6
- Current supply chain for pipelines is not sufficient to meet projected global demand
- Increasingly demanding applications favour pipe producers with high capability and knowledge (this is the case in the UK)
- Improved insulation materials for deepwater pipelines and LNG/liquid hydrogen transportation.
- Cryogenic materials for LNG infrastructure
- Future requirements for long distance gas pipelines offer high export potential
- Drive for improved efficiency in electricity transmission/distribution
- Increasing demand for electrical steels

Threats

- More dynamic overseas manufacturers exploit UK developments.
- High UK costs.
- Poor take up of sciences/maths in schools/universities.
- Business decisions driven by cost.
- UK Continental Shelf oil and gas reserves are mature. The majority of future large scale oil and gas developments will be abroad
- Perception of over reliance on gas may limit developments depending on future energy strategy
- Availability of skilled materials scientists and engineers in the UK

8.0 Recommendations

General Recommendations:

- UK knowledge in energy materials for transmission, distribution and storage has become dispersed since privatisation of the energy services. There is need to collect the available data and capture the experience of mature practitioners before retirement.
- Such information should be collated and stored, together with more recent R&D (such as the EPSRC Supergen programme) into a coordinated national Electrical Transmission & Energy Storage archive, possibly located at the recently announced Energy Technologies Institute (ETI)[ref.23]
- Current asset updating programmes should be coupled with the latest technology improvements [e.g. the EU SuperGrid and associated 'smart energy' systems] to ensure that the UK has an efficient and sustainable energy system to meet future needs.

Recommendations on Electrical Transmission and Distribution:

Electrical Equipment:

Incremental Materials Technology:

- Research on materials technologies is needed to support the application of wide-band semiconductors in electrical transmission and distribution for high power switching
- Current switchgear is bulky and intrusive. Large clearances are also necessary to withstand high steady-stage voltages, together with large volumes for arc extinction. Improved material and engineering options could significant reduce this bulk.
- More environmentally friendly dielectric materials are also required to replace the arc suppressant SF_6, which is a greenhouse gas.
- Smaller, quieter and less 'lossy' transformers require transformer core steels that support high flux densities without loss or noise. Such steels require enhanced coatings to aid noise reduction, offer component protection and extend lifetimes.

'Step change' Materials Technology:

- Development and demonstration of superconducting fault current limiters using existing High Temperature Superconducting (HTS) materials and process technology. Development of new HTS materials is a longer term R&D requirement.

Structural Materials:

- Higher strength conducting wires / cables with reduced 'sag', particularly when warm, together with fittings that can run hotter to enable overhead cables to carry more power with shorter insulating strings and within a lower silhouette. Future upgrading could include the introduction of 'no loss' superconducting cables.

Transmission of Other Energy Fuels

Emphasis has so far concentrated on electrical transmission and distribution. Alternative energy fuels (oil, gas, and hydrogen) also require transportation and distribution.

Materials R&D associated with transmission of such fuels includes development of:

- Higher strength and toughness pipeline grades of steel and a fuller understanding of microstructure and properties. Clad / composite pipes will also be introduced.
- More economic corrosion-resistant pipes for mixed gas and hydrogen transport combined with greater understanding of the metallurgical factors involved in mixed natural gas and in hydrogen transportation along current pipeline materials.
- Lower cost cryogenic materials for Liquid Nitrogen Gas (LNG) transmission and LNG / liquid hydrogen storage:

Electrical Energy Storage

'Portable power' requires energy to be carried in a variety of forms - from the ubiquitous battery packs, through intermediate sized storage for hybrid automotive power, to large scale devices that can store gigawatts of power. Again the range of technologies covers incremental developments in relatively long-standing storage methods to more ambitious 'step change" developments:

Incremental Storage Technology:

- There is need to develop superior secondary lithium batteries using chemistries that do not rely on strategically sensitive cobalt additions. The complex issue of recycling / disposing of a wide range of complex battery materials also needs addressing.
- Flow batteries/fuel cells require 'scaling up' with an emphasis on efficiency and environmentally acceptable operation. Again recycling and disposal are issues.

'Step change' Storage Technology:

- High-energy storage supercapacitors are being developed to 'demonstrator status' for hybrid drive regenerative braking systems as part of EU programmes. Similar supercapacity storage methods would allow full exploitation of fluctuating energy generators [e.g. wind turbines].
- Superconducting Magnetic Energy Storage systems (SMES) provide high storage and release capabilities over a wide range of energy levels. Future commercial opportunities look promising. A range of innovative materials research studies associated with superconducting and conventional magnetic energy storage systems are identified.

9.0 R&D priorities

Short Term Materials research Priorities [5 years]

Short-term strategic emphasis should focus on the needs of electricity network owners, plus manufacturers of niche products for the export market such as High Voltage Direct Current (HVDC) equipment for China & India. Priority national materials R&D themes should include:

- Support for implementation of eco-design transmission and distribution products. Examples include accelerated use of ester oils in place of mineral oils in transformers and removal of heavy metals from lithium-ion batteries. There is also a need to adopt a 'UK standard approach' to eco-materials.
- Development of better and more compact thermal management solutions for use with high and medium voltage equipment.
- Establishing the UK electricity industry as a knowledgeable user of electrical equipment that contains nano-materials, in particular those that are polymer-based.
- Establishing manufacturing technology for composite pressure vessel fuel storage and for advanced polymer composite components for high and ultra high voltage insulation. There is also a need for insulators with extended lifetimes and enhanced properties
- Producing affordable, low-loss transformer core steels and associated component manufacturing technology. Lower cost cryogenic materials are also a priority.
- Provision of a free-access, internet-based library of transmission, distribution and storage materials properties. This should include collation of industry knowledge plus a national measurements programme. Critical properties of superconducting materials should also be included, together with material and process modelling capabilities, material characterisation and agreed methodologies for life cycle prediction and economic cost benefit analysis.

Asscociated with security of energy supply is the complementary issue of strategic materials, including carbon fibre for composite structures, high temperature superconducting materials and even more basic materials such as copper wire. Global sources of materials are becoming increasingly stretched (and hence expensive) as developing nations such as China and India strongly enter the materials market.

Medium and Long Term Materials research Priorities [5-20 years]

Longer-term emphasis should be on evolution of the UK grid to increase capacity, reliability and efficiency and to provide opportunities for new high technology products and companies. Priority themes should include:

- Establishing a national centre of excellence in innovative materials technologies for affordable energy storage. This centre should identify and develop research priorities to cover the higher energy range of energy storage options excluding existing research focused on energy storage for vehicles. Such a Transmission Distribution & Storage (TRADS) Materials Centre might form part of the remit of the recently announced £1bn Energy Technology Institute (ETI) at Loughborough University [ref.23].
- Materials research to enable exploitation of wide-band semiconductor materials (e.g. silicon carbide) in the transmission and distribution system. Developments should include packaging technologies, high temperature supporting components (e.g. capacitors) and thermal management.
- High temperature superconducting (HTS) materials technologies for the production of cabling, fault current limiters and superconducting magnetic electrical storage (SMES). Such research should exclude development of new HTS superconducting materials.
- Materials and process development for high strength, high toughness pipelines, including coating technology and a fuller understanding of fracture mechanics behaviour. In particular, property data is required that will allow development of modified design codes for pipelines operating in low temperature regions and/or carrying liquefied nitrogen gas (LNG). Similar requirements are needed for lower cost cryogenic materials for tankage.
- As the 'hydrogen economy' grows in importance, there are materials issues associated with hydrogen generation for fuel cells and long term hydrogen behaviour of hydrogen-containing pipework and storage tanks
- Each alternative fuel option poses different material constraints. Transfer of CO_2 [e.g. for increased oil extraction and sequestration] requires specific polymer/steel pipework/containment. Mixed gas transport will involve new gas separation membranes that operate for extended periods without blockages or cross-contamination.
- For cost and security of supply reasons it would be desirable to develop cobalt-free batteries within a decade and to exploit new battery architectures. Nanotechnology provides one means of increasing electrode surface area and maintaining intimate chemical interaction between the electrolyte and electrode.
- Hybrid automotive technology will provide the stimulus for new battery/fuel cell developments within the mid-power range, with supercapacitors contributing to greater energy efficiency via regenerative braking.
- Novel materials for network sensors will increase network reliability through power management and equipment condition monitoring devices. It should be possible within a decade to provide 'distant' supervisory control. Electronic harvesting and storing of power is currently being developed and could be a commercial reality within 10 years.
- Longer term (20-year) possibilities include flow battery/fuel cell materials and circuit breaking technology that are ecologically sound, new higher temperature superconducting materials and self-monitoring / healing structures

> *"In the network of the future, materials matter and make a material difference."*

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