Alternative energy technologies

Materials UK Energy Review 2007

Report 4 - Alternative Energy Technologies

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In addition, consultation has been held with many other UK groups including the UK Energy Research Centre and the Advanced Power Generation Technology Forum.

1.0

Executive summary

The Materials UK Alternative Energy Technologies Group has undertaken a series of reviews aimed at identifying materials challenges facing renewable energy technologies.

The technologies selected were those of most relevance to the UK and include those with close links to fossil fuel heat and power technologies and those that take advantage of naturally occurring processes - namely:

- Biomass / waste to energy, hydrogen and fuel cells and:
- Wind, wave/tidal and solar power

For each technology, the research priorities to support future materials development in the UK have been identified.

The chosen technologies provide 'low carbon' alternatives to fossil fuels, though for hydrogen power this depends on the source of the feedstock. All can contribute to reducing CO_2. No single technology predominates but all play a part in meeting future demand or displacing other equipment that is more 'carbon intensive' when it comes to the end of its commercial life. Maintaining a broad portfolio of alternative energy options is critical to the future energy security of the UK.

UK Strengths

UK strengths in Alternative Energy vary depending on the particular technology. In some cases, e.g. fuel cells, UK has leading-edge manufacturers (e.g. Johnson Matthey Fuel Cells & Rolls-Royce Fuel Cells), whereas in others UK strength lies in the deployment of technologies from overseas, e.g. offshore wind farms. The UK is however able to support future energy options via well established manufacturing, servicing and integrated systems capabilities and through technical consultancies. UK strength also lies in the strong links between universities, Research & Technology Organisations (RTOs) and industry. These links are critical and must be maintained and grown.

Research Priorities

Generic 'alternative energy' research priorities are identified below. Some priorities can be met within UK's current capabilities; some require expansion of UK research activities, while others are best addressed via overseas collaboration. High priority should be given to the following topics:

Structural Materials [Load-bearing]

- Light-weight/high strength Fibre Reinforced Polymer (FRP) composite wind and tidal turbine blades for large scale, low cost designs that are able to resist high fatigue loads and harsh offshore environments
- Continued development of innovative material designs and processing techniques for wind/wave/tidal turbines – such as sandwich constructions, composite joints, FRP pre-forming and infusion techniques
- Sub-system component development of fuel cells
- High strength, corrosion resistant heat exchanger alloys and coatings for biomass & waste systems

Functional Materials [Active surfaces / electrical]

- New and improved materials for fuel cells, including electrolytes, electrodes and interconnect materials
- Separation membrane technology (e.g. for H_2/CO_2 separation), materials for hydrogen storage

Materials processing, fabrication and integration

- Advanced processing of silicon and thin film GaInP/GaAs for photovoltaic cells to reduce costs
- Advanced processing of fuel cell materials for both high and low temperature applications
- Development of continuous manufacturing processes for materials that are currently batch produced and require more consistent quality of manufacture
- Development of 'in-process' inspection techniques to ensure the supply of high quality components
- Development of repair techniques that can ideally be deployed 'in-situ'.

Executive summary

Environmental Resistance and Protective Systems

- Paints – e.g. antifouling for wave / tidal components
- Coatings–e.g. corrosion protection for biomass/waste heat exchangers, oxidation/hot corrosion resistance in gas turbines/engines, high temperature fuel cell components, antireflective coatings for PV cells, etc.

Life Cycle Modelling:

Modelling offers a short cut to improving component design and is an invaluable tool for management of the energy system in service. Modelling areas include:

- Behavioural modelling of wind and tidal turbine blades
- Thermo-mechanical behaviour of heat exchangers in biomass combustion and gasification systems
- Operating behaviour of low and high temperature fuel cell components
- Improved reliability and reduced uncertainty through development of test and modelling methods for lifecycle analysis/fatigue performance of constituent materials, sub-components and major structures such as blades
- Development of test and modelling methods for materials characterisation in harsh environments.

Generic Material Requirements:

Many technologies share common material development requirements:

- Condition monitoring and 'smart sensors' are also critical for assessing environmental conditions and material degradation in extreme locations [such as offshore wind farms]. Data from such sources provides input for modelling/validating service behaviour. Monitoring technologies also facilitate scheduled maintenance and lead to reduced operating and maintenance (O&M) costs.
- Development of 'field deployable' non-destructive evaluation (NDE) techniques enables accurate and rapid defect detection of damage/defects [e.g. in wind turbines or wave / tidal devices]
- Development of standards and certification procedures
- Testing and characterisation procedures
- Repair, rejuvenation and recycling of expensive materials
- Investigation into fundamental failure mechanisms in advanced materials. Such studies should include effects of environment and micro- / nano-scale flaws on material durability.

In summary, the main challenges that alternative energy systems have to overcome to reach full commercialisation within the next decade are **durability, reliability and cost.**

Eco Considerations and Sustainability

As production capacity increases for each alternative energy technology, greater attention has to be given to material processing and potential toxic emissions/waste. Such considerations are particularly relevant for newer, high performance materials. It is not sufficient for finished products to be environmentally safe and chemically inert. The environmental implications for new materials and manufacturing technologies need to be considered throughout the whole supply chain.

High volume production will reduce the ready availability of many specialist materials. Limited access to carbon fibre materials for wind turbines is already being observed. Similar limitations are likely to affect exotic materials such as indium as used in some transparent conducting oxides for thin film PV production and more 'common' materials such as copper for generators. Readily available alternative materials need to be developed.

Legislation and Energy Security

Alternative energy systems will require legislative incentives and funding initiatives before they become readily available at commercially attractive costs.

Environmental legislation is increasingly concerned about product end-of-life management. Automotive and electrical/electronics sectors have already been set mandatory European recovery and recycling targets. Introducing legislation into the alternative energy sector may prove difficult, given the diversity of technologies involved, but further constraints are likely. It would be unacceptable if "green" sources of power were to cause environmental burdens during later decommissioning and disposal. Research into end-of-life management will be critical in the next 20 years. In particular, research is required into cost-effective recovery and recycling of materials and into avoiding subsequent disposal through landfill.

2.0 Introduction

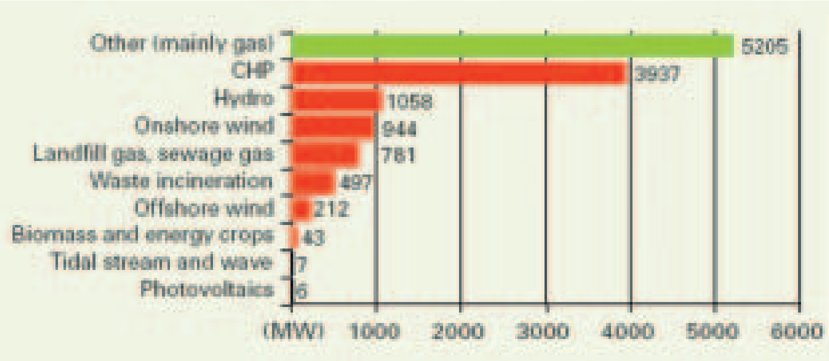

Fig.1. Generation Plant Currently Connected to UK Distribution Network [ref.1]

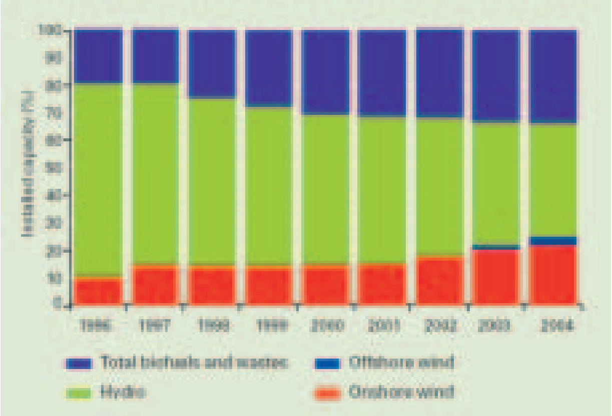

Fig.2. Contribution of Different Technologies to UK's Overall Electricity Generation from Renewable Sources *[ref: DTI Energy Challenge 2006]*

Renewable energy is an integral part of the Government's strategy for tackling climate change.

In its 2006 Energy White Paper [ref.1] the government proposed a range of measures to enable 20% of UK electricity to come from renewable sources by 2020.

That target will only be achieved by significant advances in all available technologies and in associated materials and processes. This report, carried out by specialists in consultation with their communities, summarises the Material R&D priorities necessary to achieve full technical and manufacturing readiness.

Renewable energy can be connected into the electricity network either at the national transmission level [the 'grid'] or at the more local distribution level. Technologies such as large offshore windfarms are more suitable for direct connection into the transmission grid, whereas some small-scale offshore wind turbines and most onshore facilities are connected to local distribution networks. Other local renewable energy sources [hydro, waste incineration, photovoltaics etc.] are almost exclusively connected into the distribution network. Fig.1 illustrates the range of energy sources currently connected to the UK distribution network. Local distribution is dominated by non-renewable gas and combined heat and power (CHP), with all combined renewables currently accounting for little more than 3,500 MW.

Fig.2 illustrates how current UK renewable energy trends have developed [ref.1]. Hydropower has reduced at the expense of wind power and biofuels / waste. The above trends are historic and future projections should be treated with caution. For example, despite the decreasing trend for hydropower, if the proposed Severn Barrage were built [at an estimated cost of £14bn] then that one hydropower facility alone would be capable of generating 5% of UK's current energy needs by 2020 [ref.1 p.100].

Very different technical designs and associated materials developments are needed to exploit the differing energy sources. Subsequent chapters address the materials priorities needed for the following technologies:

- Section 3: Wave & Tidal Power
- Section 4: Wind Power
- Section 5: Biomass Technologies

Materials development for the three technologies identified above are essentially incremental in nature. The remaining energy sources would introduce 'step change' technology in which reliance on fossil fuels is replaced by a 'hydrogen economy' and/or one 'powered by the sun'. Hydrogen power would require an extensive new production and distribution infrastructure, which would be dependent on innovative materials technology to store the portable 'fuel of the future' and to convert it into power. The materials R&D priorities for future hydrogen usage are covered in:

- Section 6: Hydrogen Power
- Section 7: [Hydrogen] Fuel Cells

Harnessing the power of the sun will require sophisticated functional materials and processing techniques to convert solar energy into electrical power. Such energy conversion could be carried out locally with excess capacity fed back into the distribution network. The materials issues associated with electrical distribution are covered in an associated report (ref.2) while Materials R&D priorities for solar power are addressed here in:

- Section 8: Solar Energy

References:
1 DTI Energy Review Report July 2006 "The Energy Challenge" Cm 6887
2 Mat UK Energy Materials Review - R&D Priorities for Energy Transmission, Distribution and Storage

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3.0

Wave and tidal power

Tidal power arises from the gravitational pull of the sun and moon causing water levels to change. This change in level creates currents and that energy can be harvested by the use of sub-surface turbines. Tidal velocities as low as 0.5 m/s can be used to drive a turbine, though velocities of 2-4m/s are more typical. A tidal turbine can produce more than four times the energy per square metre of a wind turbine rotor.

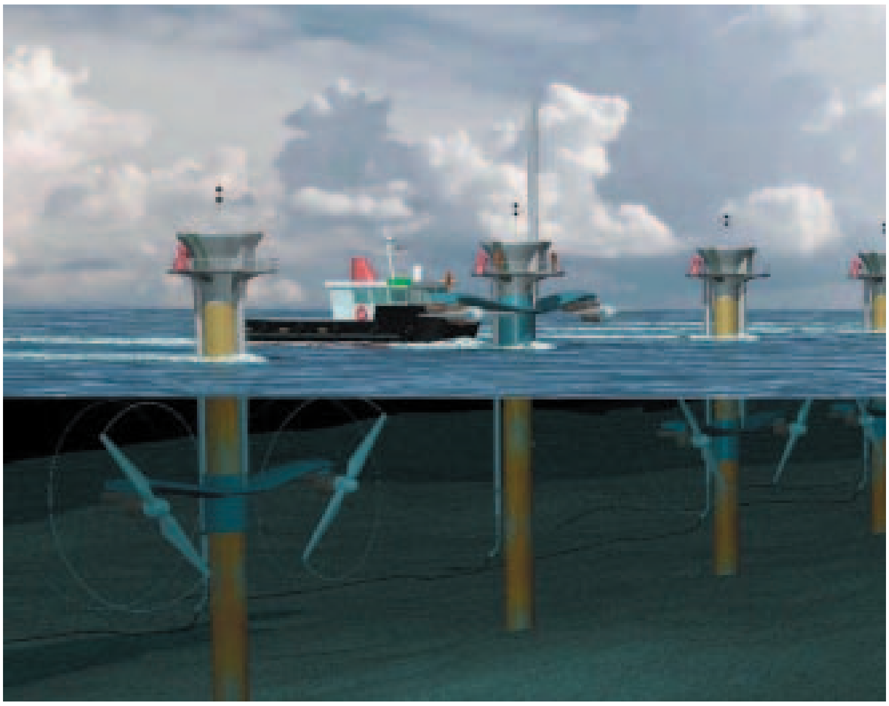
Moreover, the movement of earth, sun and moon are cyclical and therefore predictable, aiding the planning of energy production. Tidal power is essentially environmentally friendly, renewable and emission-free.

Similarly, as wind moves across the surface of the sea it creates ripples, which grow into waves and ultimately become great ocean swells. Once formed, ocean waves can travel great distances with minimal loss of energy until they break on the shore. The Western coast of the British Isles is one of the highest wave energy environments on the planet with 60-70kW/m waves in deep water off the Western Isles. This energy levels falls 15-20kW/m at the shoreline due to the effects of bottom friction and wave breaking.

The World Offshore Renewable Energy Report for 2004-2008 forecast a global capacity of 20.9MW tidal turbine power in 2004-2008 with 84% of that power developed around the UK. The Carbon Trust estimated that 2-5 GW of wave and tidal energy could be installed across Europe by 2020 following capital investments of the order £2-5bn. The longer-term potential for worldwide wave and tidal energy is open to question as estimates vary greatly. A European Commission Joule project estimated that more than 1000TWh a year of global tidal power could be produced with half being available for the EU. Wave and tidal power represents a significant source of renewable energy. Production of tidal turbines is projected to double every three years up to 2020. Up to 100 tidal turbines could be manufactured each year by 2012 with some 600 tidal/wave turbines in UK waters alone by 2020.

UK is in a strong technical position to take a sizeable portion of the world tidal turbine market. It leads in turbine technology, has many coastal locations for placement of tidal turbine farms and has a strong marine and offshore industry heritage to support the industry.

Photo: courtesy of Marine Current Turbines



3.0

Wave and tidal power

3.1 State of the art in materials and structures for turbine design

There are two main types of sub-sea turbine - the rotary turbine and the hydroplane.

An example of a rotary system is the ‘state of the art’ 1.2MW twin rotor Seagen tidal flow generator in Northern Ireland that is planned to come on line in the latter part of 2007. The Seagen turbine project has two 16m-diameter twin-bladed turbines that are lifted out of the water and turned horizontally for maintenance. Aviation Enterprises Ltd. UK manufacture the 7.5m composite material blades. The variable-pitch rotors optimise efficiency no matter in what direction the tide is flowing.

The supporting column is made of rolled steel that is welded to form monopiles that are 3m diameter at the top and 4m diameter at the bottom. These are inserted into holes or can be driven into the seabed. Cathode protection and painting are used to protect the monopiles from corrosion. Use of stainless steels or other corrosion resistant alloys are used in small volumes where the cost of increased strength and corrosion resistance can be justified.

Carbon fibre composites are the only practical material for tidal turbine blades in order to reduce the weight of these moving parts, thereby improving efficiency and reducing the weight of the supporting structure, gearboxes and hubs. Blade construction generally uses a carbon fibre spar as the main load bearing structure. The spars are mainly unidirectional along the blade length but can also contain +/-45 plies or woven plies to resist blade pitching and torque. Skins are manufactured from GRP with aramid layers for impact resistance.

Hydroplane turbines have also been installed. The angle of attack of these devices is altered to create lift (and drag) as the hydroplane moves repeatedly up and down. This linear motion is used to drive hydraulic cylinders that in turn drive a generator. Hydroplanes are generally composite structures with a steel supporting structure with points for attachment to a gravity base. The Stingray tidal generator was the first of its type to be installed off UK shores.

Other approaches to turbine design exist using floating rotating turbines anchored to the seabed by chains. This arrangement could reduce the costs associated with mounting turbines on anchored masts. Another design encloses the turbine in a cowling similar to an aircraft jet engine.

One of the key engineering components within a turbine is the gearbox. The planetary gears have compliant mountings to avoid excessive loads being transferred to any one gear. Natural water-cooling is used to maintain a low working temperature for the gearbox. While most parts are steel, the fairings and housings are GRP.

‘Seaflow’ tidal current turbine *[Courtesy of Marine Current Turbines].*

3.2 State of the art in materials and structures for wave device design

Wave power can be harvested using a range of devices, such as articulated rafts, 'nodding' structures, compressible floating bags, tethered buoys, bottom-standing oscillating water columns, over-spilling systems and submerged pressure chambers.

The Pelamis Wave Energy Converter (WEC)
[Courtesy: Ocean Power Delivery].

There are more than 50 different wave conversion technologies being developed worldwide. The devices can be subdivided into 'shallow water' systems that are built near-shore or into the shoreline and 'offshore systems' designed for water depths of tens of metres. There are demonstrations at the 500 -750 kW scale, but the technologies have yet to become a commercial reality.

Ocean Power Delivery's Pelamis, and the Danish Wave Dragon are both offshore devices that serve to illustrate the current 'state of the art'.

Pelamis is a freely floating hinged contour device with 4 tubular sections connected by 3 hinges. The 4 sections move relative to each other in both pitch and yaw; the hinges then convert this motion by means of a digitally controlled hydraulic power system. The total device length is 150m, with a tube diameter of 4.63m. Pelamis is of steel construction using standard fabrication techniques and equipment. The device is slack-moored and, within the mooring constraints, is free to turn into the wave direction.

Wave Dragon combines a double curved overtopping ramp and two reflector arms, which focus energy onto an overtopping basin where a number of modified Kaplan-Turbines are used to drive generators. This device is also slack-moored and able to swivel in order to face the wave direction. The structure is built using a combination of steel and reinforced concrete, which can be built using standard construction techniques at most shipyards. Wave Dragon's large size means that it requires a large construction yard for assembly.

A number of designers of wave power devices are considering use of composites and face similar materials challenges to those described for tidal turbines. The materials in wave device sub-systems, such as gearboxes, generators and electrical systems are also subject to the same aggressive conditions experienced by tidal turbines.

3.0

Wave and tidal power

3.3 Structural and material challenges

Wave and tidal power equipment operates under high fatigue loading in cold seawater conditions for periods in excess of 20 years.

The main structural requirements are high static strength and stiffness. Tidal turbine blades require a high fatigue life to achieve long life expectancy with minimum inspection and maintenance. Structural material challenges are similar for both rotary and hydroplane designs. Structures have to withstand long-term underwater operation, seabed erosion and damage from flotsam, vessels and trawler nets.

Tidal turbines structures tend to be over-designed to take account of salt corrosion and heavy or turbulent tides. This results in performance penalties. Methodologies to optimise wave/tidal power performance are still required.

Cavitation can occur when pressure gradients form vapour bubbles on blade surfaces. Collapse of these bubbles creates vibration and imparts local stresses that can cause blade damage and reduce efficiency. Blade designs and coatings can help minimise cavitation damage.

The need to minimise biofouling is a major design consideration. Preventative measures include painting or inclusion of copper powder in resin formulations as a blade skin. Many of the wave power structures [e.g. the tower, gears etc.] are fabricated from carbon steel that has a finite life when operated in seawater. Corrosion protection corrosion is an ongoing task for the steel parts and regular maintenance and inspections are required. Such inspection can be costly especially when divers or robotic observation vehicles (ROVs) are required.

3.4 R&D Needs for Materials and Structures

Materials are well established for current turbine designs but future (5-10 year) developments will need new materials and manufacturing technologies:
Resistance to seawater degradation and the ability to withstand high fatigue loadings are the two main design drivers for composite resin systems used in wave turbine blades. Unfortunately, available resin systems were not developed specifically for such wave turbine applications. Resins need to be developed for low cost manufacture as well as in-service issues. Wave turbine blades tend to be relatively thick and are manufactured using out-of-autoclave vacuum bag procedures. Resins must be able to accommodate the exotherms that can be generated in thick blade interiors and they must also withstand anti-fouling paint.

Wave overtopping on the Wave Dragon device
[Courtesy: Wave Dragon. Photo: Earth-vision.biz]

There is substantial experience of the effects of seawater on the long-term properties of composites [from the boat-building industry] but little experience of fatigue behaviour in thick structures. Most composite fatigue data is from thin laminate structures used in aerospace or rotorcraft applications. The design life of a turbine structure is in excess of 20 years, while monopiles are designed for even greater lifetimes. Behaviour of welded and bolted joints must also be considered.

Some turbine configurations are not removable from the sea for maintenance and require the use of ROVs. Integrated inspection techniques combined with structural health monitoring are needed to verify structural integrity. Use of embedded fibre optics is increasing for wind-turbine blade condition monitoring and for subsea oil and gas risers. Similar technology needs to be applied to wave turbine blades and towers. Use of smart materials/structures that incorporate actuators and sensors would allow materials to respond to external stimuli and achieve greater turbine blade or hydrofoil efficiency. A multi-disciplinary approach is needed to study actuation and fluid-structural interaction.

The effect of tidal turbines on marine environment is thought to be benign. Turbines rotate at 10-20rpm and although noise is generated it is not thought to affect marine life. In addition, no environmentally damaging fluids are used within the subsea structure.

3.5 UK capabilities

UK is a world leader in marine energy technology but commercial progress has been slow. A growing number of small start-up companies and academic institutes are developing wave and tidal stream devices. In addition, establishment of the European Marine Energy Centre (EMEC) in northern Scotland allows pilot scale wave and tidal stream devices to be tested in an offshore facility. EMEC is the only multi-berth purpose-built test facility in the world for evaluating wave and tidal technologies. The New And Renewable Energy Centre (NAREC) is another testing facility at Blyth. UK can claim a significant degree of expertise in wave/tidal power development. However gaps in UK materials capability still exist:

- Lack of a dedicated composite materials R&D programme, addressing both fundamental materials properties issues as well as large-scale manufacturing.
- There is a need for a greater understanding of the fatigue behaviour, durability and mechanical performance of large composite structures in the marine environment, especially for sub-sea structures.
- The developing world market for marine energy devices demands high-volume manufacturing techniques capable of producing consistent quality items based on clearly understood design rules.

The Pelamis Wave Energy Converter (WEC)
[Courtesy: Ocean Power Delivery].

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Structural Health Monitoring

4.0 Wind power generation

Manufacture of wind turbines on a commercial scale starting in the 1980s. It is currently the fastest growing sector of the power generation industry, with anticipated industry expansion rates consistently being exceeded since the early 1990s.

As the wind energy industry has grown, electricity generated by wind power has shown a dramatic fall in cost. The average cost of production from a coastal turbine has decreased by more than 50% within 15 years - from ~8.8€ cents/kWh in the mid-1980s to 4.1€ cents/kWh for a modern 1 MW turbine. Wind power is already cost-competitive with some new coal-fired power stations and in some areas can challenge gas, currently the cheapest option. Despite this progress, wind power has some way to go before it fulfills its potential as a large-scale supplier of electricity.

4.1 Overview of the Wind Power Market

Drivers

Key issues driving growth in wind generated power include:

- Gradual depletion of fossil fuel reserves
- The need to ensure security of power supply via reduced energy import dependence
- Electricity price rises
- Need to reduce emissions linked to global warming [CO_2, green house gases (GHGs)]
- Government policy and direction
- Increased UK and global energy demand

Current and Future Market Sizes

UK

The UK Government set a target of a 60% reduction in carbon emissions by 2050 and introduced legislation to encourage uptake of renewable energy. The Renewables Obligation (RO) was introduced in April 2002 and requires all electricity suppliers to source 10% of their supply from renewables by 2010. In 2004 that target was revised to 15% of supply by 2015.

Wind is currently the most technically and economically developed renewable energy and is expected to make up around 75% of the 10% target by 2010. This equates to around 8,000 megawatts (MW) of capacity, which will be derived from onshore and offshore farms. To meet the 2010 target a further 1,500 onshore turbines (assuming an average size of 2MW) need to be built in addition to the 1,414 turbines that have already been installed. Offshore turbines are generally larger and more powerful (>3MW) so fewer (1,300) will be needed.

The UK has recently broken the 2 GW threshold of electricity from wind power, around 1.5 % of the total UK electricity supply. The level of electricity from wind power has doubled in little more than a year and is now sufficient to provide more than 1 million homes with power [ref. Renewable Energy Statistics Database www.restats.org.uk/2010_target]

Europe

In 1997 the European Wind Energy Association (EWEA) adopted targets set by the European Commission's White Paper [1] on renewable sources of energy for 40 GW of wind energy capacity by 2010.This target was revised 3 years later to 60 GW by 2010 [2]. However, even this revised forecast has proved to be conservative. Latest EC figures [3] indicate that wind power capacity in Europe could reach 69.9 GW by 2010. The target now adopted by the EWEA for 2020 is for 180 GW of power, of which 70 GW would be generated by turbines located offshore. EWEA's target for European electricity generation from wind is set at 5.5% in 2010 & 12.1% in 2020 [4]. This is equivalent to the electricity needs of more than 195 million people.

4.0 Wind power generation

4.2 Wind Turbine Technology

The basic design of wind turbines has not changed significantly since the early 1980s. Most wind turbines have upwind rotor blades that are actively yawed to ensure alignment with the wind direction. Figure 1 shows the components of a conventional wind turbine, together with an indication of the percentage of the overall wind turbine cost.

The three-bladed wind turbine configuration is the most common. It typically has a separate front bearing with a low speed main shaft connected to a gearbox that provides an output speed suitable for a four-pole generator. For the largest wind turbines, the blade pitch is varied continuously under active control to regulate power under high operational wind speeds. A nacelle housing encases the front bearing and pitch control system and the entire turbine drive train is supported on a mainframe construction mounted on the tower.

The drive train in Figure 1 shows the rotor attached to the main shaft driving the generator through the gearbox. Significant recent developments in basic design configuration have seen the advent of direct drive generators, where the gearbox is removed and the rotor is used to drive the generator directly. Hybrid arrangements involving a single stage gearbox and multi-pole generators are also now appearing.

The main design drivers for current wind turbine technology are:

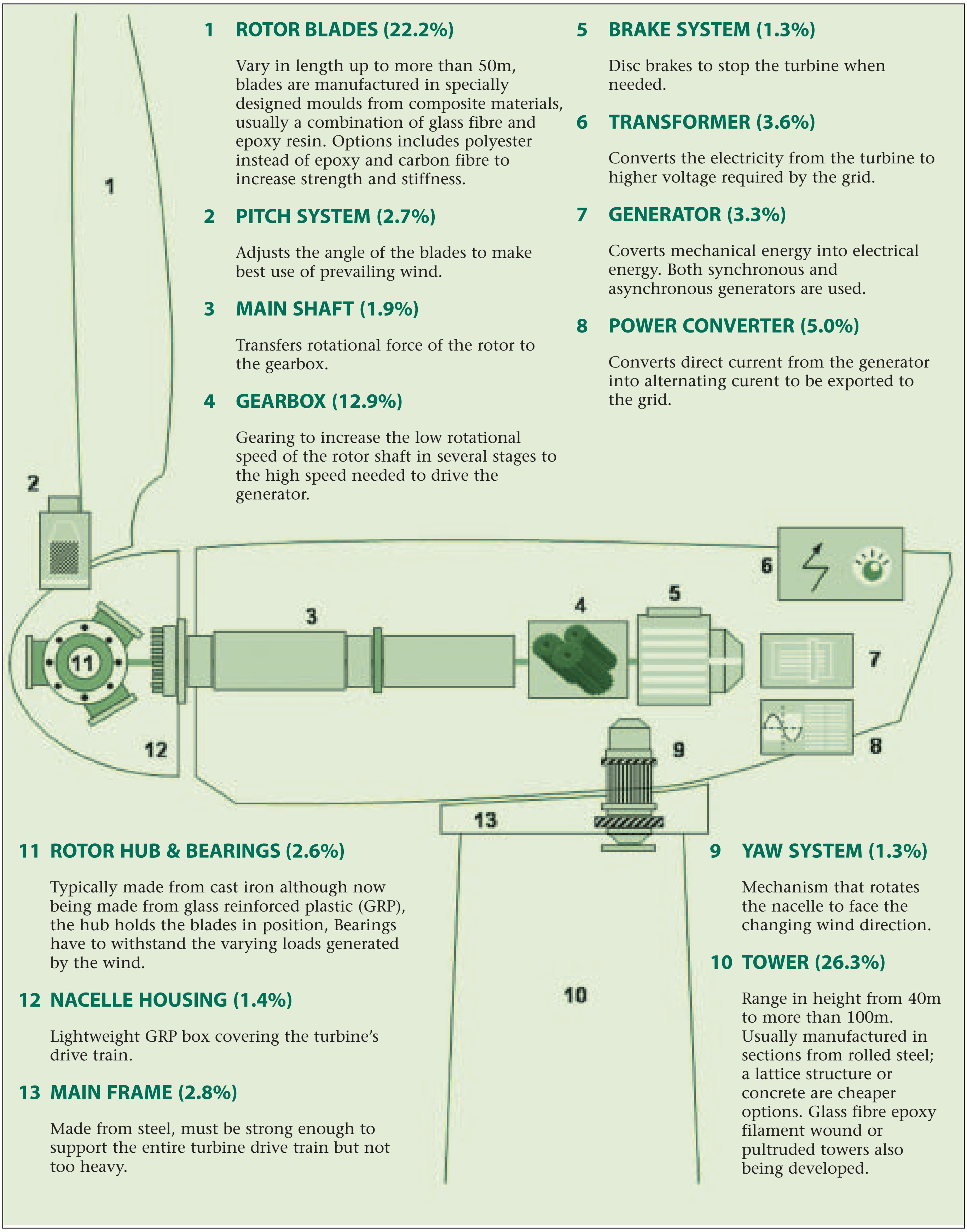
- Improved technology for low and high wind sites
- Grid compatibility
- Aerodynamic and acoustic performance
- Low visual impact
- Offshore expansion

Although the proportion of offshore wind turbines is less than 1% of the total installed capacity, the latest wind turbine developments are driven by the offshore market. This means that the current technology driver is to make wind turbines as large as possible with the following key issues:

- Low mass turbine and nacelle arrangements
- Large blade technology and advanced composite engineering allowing enhanced exploitation of low wind sites. For high wind sites, smaller blades, shorter towers and reinforced supporting structures are used
- Design of offshore foundations, wind trubine erection and maintenance

Using current wind turbine architectures, it will be extremely difficult to build turbines with an output greater than 5 MW because the cost of the turbine will exceed the value of the energy output. To meet this challenge lower cost advanced materials, new designs and more cost-effective manufacturing/production processes are seen as critical. Such developments will require a significant amount of R&D if larger, more reliable designs are to be realised.

The following sections provide detail on design issues, material choice and future technology/material trends for the major component parts of wind turbines. Two cross-cutting themes, applicable to all materials and structures are outlined in Annex A. These are Non-Destructive Inspection (NDI) and Structural Health Monitoring (SHM).



1 ROTOR BLADES (22.2%)

Vary in length up to more than 50m, blades are manufactured in specially designed moulds from composite materials, usually a combination of glass fibre and epoxy resin. Options includes polyester instead of epoxy and carbon fibre to increase strength and stiffness.

2 PITCH SYSTEM (2.7%)

Adjusts the angle of the blades to make best use of prevailing wind.

3 MAIN SHAFT (1.9%)

Transfers rotational force of the rotor to the gearbox.

4 GEARBOX (12.9%)

Gearing to increase the low rotational speed of the rotor shaft in several stages to the high speed needed to drive the generator.

5 BRAKE SYSTEM (1.3%)

Disc brakes to stop the turbine when needed.

6 TRANSFORMER (3.6%)

Converts the electricity from the turbine to higher voltage required by the grid.

7 GENERATOR (3.3%)

Coverts mechanical energy into electrical energy. Both synchronous and asynchronous generators are used.

8 POWER CONVERTER (5.0%)

Converts direct current from the generator into alternating curent to be exported to the grid.

11 ROTOR HUB & BEARINGS (2.6%)

Typically made from cast iron although now being made from glass reinforced plastic (GRP), the hub holds the blades in position, Bearings have to withstand the varying loads generated by the wind.

12 NACELLE HOUSING (1.4%)

Lightweight GRP box covering the turbine's drive train.

13 MAIN FRAME (2.8%)

Made from steel, must be strong enough to support the entire turbine drive train but not too heavy.

9 YAW SYSTEM (1.3%)

Mechanism that rotates the nacelle to face the changing wind direction.

10 TOWER (26.3%)

Range in height from 40m to more than 100m. Usually manufactured in sections from rolled steel; a lattice structure or concrete are cheaper options. Glass fibre epoxy filament wound or pultruded towers also being developed.

Note - Percentages contribution to overall cost based on a REpower MM92 turbine with 45.3 m length blades & 100m tower. [Source: Wind Directions - Jan./Feb. 2007 bulletin - "Focus on Supply Chain", European Wind Energy Association]

Figure 1: Components of a wind turbine and indicative percentage of overall cost

4.0

Wind power generation

Blades

Wind turbine blades are complicated structures built from a large number of materials and exposed to complex aerodynamic loading and environmental conditions.

Historically the vast majority of wind turbine blades have been constructed from a combination of:

- Wood (e.g. birch, balsa) and:
- Glass fibre-reinforced plastic (GRP) composites

Initially glass fibre reinforced polyester systems were used but now epoxy-based resin systems predominate. Many of the components are adhesively bonded. There has also been recent interest in the use of natural fibre composites as sustainable alternatives to synthetic polymer matrix composites. Material selection is heavily influenced by:

- Blade size
- Number of blades
- Turbine location and hence weather conditions and:
- The operating speeds of the rotor

With increased importance on mass reduction, the overall relationship between blade mass and diameter is becoming slightly less than cubic. This trend will be hard to maintain as rotors continue to get larger. Increased size, without a radical change in design concept and material properties, will lead to much higher internal material stresses. This will necessitate higher specific strength materials and/or more compliant components. If components bearing heavy dynamic loads are made of flexible materials, then the forces acting upon them are not transferred to the supporting structure. Hence dynamic forces are averaged out, leading to significantly lower fatigue loadings.

The higher tip speeds of offshore wind turbines require a reduction in the ratio of blade projected area to rotor swept area [i.e. slimmer blades]. Reduced blade area will only allow reduced blade mass if materials of sufficiently high specific strength are available; hence the increased use of carbon fibre-reinforced plastics (CFRP) in modern, large blades. Increased automation in blade manufacture - from hand lay-up to Resin Transfer Moulding (RTM) and pultrusion with accompanying cost reduction - has led to wider acceptance of CFRP.

Innovative composite sandwich structures are increasingly being used for primary blade structures. The outer skins are made from GRP/CFRP, while the core materials are typically polyvinyl chloride (PVC) or bismaleimide (BMI), balsa wood and less frequently honeycombs (e.g. Nomex) for their inherent high stiffness and strength at low areal weights. However a major disadvantage of sandwich constructions compared to monolithic materials is that they are more prone to delamination/failure because of weak interfaces between adjacent materials with very different stiffness and strength properties.

Blades contain a multitude of adhesive and mechanical joints between similar and dissimilar materials. Localised shearing and bending effects can lead to severe induced through-thickness shear and normal stress concentrations that can significantly affect the static and fatigue strength of joined sub-components. Key requirements are composite sandwich constructions and joints/adhesives with improved damage tolerance, as well as crack-stopping characteristics and improved load introduction techniques.

It is common practice to design large FRP rotor blades according to design codes and models based on linear-elastic fracture mechanics. Shortcomings in state-of-the-art numerical tools and existing composite material models result in high levels of uncertainty that lead to conservatism in design and blades of unnecessarily high weight and cost.

Wind turbine blades are subjected to severe fatigue loads. The severity lies not only in the magnitude of the forces but also the number of fatigue cycles the blade will see in its 20-year lifetime [typically 107 cycles]. Although FRP materials have excellent fatigue properties, much work is still needed to understand how these materials perform under fatigue loading and particularly compression-dominated fatigue. It is also crucial to be able to predict how these materials and structures will behave when they contain either imperfections introduced during manufacture/processing or damage induced during the service life. Again improved fatigue modelling, design criteria and design procedures are needed to optimise use of composite materials in large wind turbine blades.

Nacelle Housing

The nacelle housing provides an outer frame protecting the turbine machinery from the external environment. The nacelle is typically made of GRP with steel reinforcements and the housing is mounted through rubber dampers to the main frame with steel supports.

Hub

The hub serves as a base for the rotor blades as well as a means of housing the control systems for the pitch mechanism. The latest wind turbines have threaded bushes adhesively bonded into the root of the blade, which then allow the blade to be bolted to the hub. Hubs are typically fabricated from cast iron alloys due to the complicated component shape. The hub material must be highly resistant to metal fatigue, which therefore precludes the use of welded constructions. In order to reduce hub weight and increase fatigue performance, the hub and shaft combination has recently been manufactured using preform-liquid GRP composite moulding techniques. Another benefit of a combined hub and shaft component is that the bolted connection between hub and shaft can be eliminated, again reducing weight, and manufacturing costs associated with drilling holes of tight geometrical tolerances. The use of composite materials allows directional 'tuning' of material properties facilitating further weight reductions. Although prototypes have been fabricated and products/techniques patented, commercial use of FRP moulded hub and shaft components is some way off.

Main Shaft

The main shaft of a wind turbine is typically forged from hardened and tempered steel. Future developments will look to fabricate shaft components from FRPs (Section 3.3) in order to reduce weight but widespread use is likely to be long term.

Gearbox

The gearbox is one of the most important components in a wind turbine. Situated between the main shaft and the generator, its role is to increase the slow rotational speed of the blades (in several stages) to the high speed needed to drive the generator. The trend toward larger wind turbines has led to expensive gearboxes. Multi-generator drive train configurations can reduce the cost for large wind turbines while increasing energy capture and reliability.

Gears are typically fabricated from carbonised steel alloys and the teeth are case-hardened and polished to provide enhanced surface strength. The fatigue and wear properties of steel alloys used in gearboxes are critical.

Direct drive generators are being introduced into recent power train architectures, thereby reducing cost and maintenance problems. Future development is anticipated in the medium to long term.

Tower and Foundations

Support towers are commonly made in tubular steel with a tapering wall thickness and diameter from the base to the top of the tower. Concrete towers, concrete bases with steel upper sections and lattice structures are less frequently used. GRP filament wound towers recently been trialled, offering lighter weight for ease of installation.

A key area of research is cost-effective foundation designs for offshore turbines. The general consensus is that steel is a far more competitive material than concrete for larger offshore wind farms. Most foundation designs require minimum attention until at least 15 metres water depth. Corrosion is not a major concern with offshore steel structures. Experience from offshore oilrigs has shown that they can be adequately protected using cathodic (electrical) corrosion systems. Painted surface protection is routinely delivered for offshore wind turbines, with a higher protection class than onshore turbines.

Generators

Mention was made previously [section 3.5] to direct drive generators. Hybrid arrangements involving a single stage gearbox and multi-pole generators are also now appearing.

Increasingly, High Temperature Superconducting (HTS) generators are being introduced in which conventional copper rotor coils are replaced by HTS materials. These windings carry greater current density and hence produce high magnetic fields. Current superconducting generators can match the power output of a conventional generator at around one-third of the size and half the weight. Transportation and installation costs are therefore less. Electrical losses in superconducting wires are also negligible and the noise profile is reduced.

4.0 Wind power generation

4.3 Operating Environments

Wind turbines are located on high ground in remote areas in order to benefit from strong winds. Wind turbine components must be robust enough to withstand such harsh conditions.

Low Temperatures

Temperatures as low as -40 °C can be experienced by materials used in wind turbine construction. Steel components can become brittle at such low temperatures. The matrix and fibres in composite materials have different coefficients of thermal expansion (CTE) resulting in thermally induced stresses that can lead to matrix microcracking which reduce component stiffness and provide paths for moisture ingress.

Thermal shock can damage electrical equipment including the generator and yaw system. The viscosity of gearbox lubricants and hydraulic fluids increases during long-term exposure to cold weather. Damage is caused to gears on start-up after extended stationary periods because the oil is too viscous. Seals and rubber mounts also perish over time in cold climates. Correct selection of materials for turbine components exposed to cold climates is therefore essential. Nickel and aluminium alloys offer improved strength over steel at low temperatures. Composites have yet to see widespread applications in cold climates. Mismatch in CTE can be accommodated by careful selection of fibre and resin combination.

Hot/Wet

In hot climates, turbine blades are made from epoxy-based composite materials that are resistant to heat and ultraviolet light. Although blades are sealed, moisture ingress via damaged painted or gel-coat surfaces can reduce the glass transition temperature of the resin, impairing mechanical performance. Swelling may also lead to dimensional changes.

Salt spray is particularly harsh on turbine components. Paint sealants and nacelle designs that inhibit penetration of salty air are used to protect the turbine, generator, blades and support tower from corrosion. Further work is needed to understand the mechanisms of long-term salt spray exposure for turbine materials, especially composites. Measurement and prediction of material mechanical properties subjected to long-term exposure under marine environments is of particular importance. Accelerated ageing techniques are also needed.

4.4 Priorities for Research and Development

The European Wind Energy Association's (EWEA) Strategic Research Agenda [5] identified a number of 'showstoppers', barriers and bottlenecks to wind energy development. Showstoppers are issues of such importance that, if not addressed, they could halt wind energy progress altogether. Barriers are physical limitations in current technology that should be overcome in the medium- to short-term and bottlenecks are issues that can be overcome through additional short to medium term R&D. The following is summary of the critical materials technologies:

- Showstoppers:
  Availability of robust, low-maintenance onshore turbines and lack of R&D into increased reliability and availability of offshore turbines
- Barriers:
  (i) Integrated design tools for very large wind turbines operating in extreme climates,
  (ii) State-of-the-art laboratories for accelerated testing of large components under realistic climate conditions
  (iii) Standards and certification for design criteria, components and materials
- Bottlenecks:
  Development of component design tools and rapid finalisation of ongoing standards

Bearing in mind the EWEA findings the following priority areas for wind turbine materials have been identified: Timescales: Short (0-5 yrs.); Medium (5-10 yrs); Long (10-20 yrs.)

- Improved reliability and reduced uncertainty through development of test and modelling methods for lifecycle analysis/fatigue performance of materials, sub-components and major structures [i.e. blades] - Medium term
- Reductions in operating and maintenance (O&M) costs through development of structural health monitoring technologies - Medium-to-long term
- Development and application of NDI techniques for more accurate and rapid defect detection - Short-to-medium term
- Continued development of innovative material designs and processing techniques e.g. sandwich constructions, joints, FRP pre-forming and infusion techniques - Short-to-medium term
- Development of test and modelling methods for materials characterisation in harsh environments - Short-to-medium term
- Development of standards and certification procedures - Short-to-medium term
- Development and application of coatings to reduce drag and improve environmental performance - Short-to- medium term

4.5 UK Capability Gaps

UK has the skills and resources for developing commercial wind farms in a cost-effective manner. However there are gaps in UK capability compared to other leading wind power nations. Some of those areas are highlighted below:

- Lack of large scale manufacturing capability in the UK:

  - There is currently one large blade manufacturer based in the UK (Vestas) who export blades mainly into the American and European markets.

  - No established UK turbine manufacturers. The majority of wind turbine components are imported.

* Lack of test facilities for accelerated testing of large components (e.g. blades) under realistic environmental conditions. This limitation is critical as wind turbine blades continue to increase in size. The New and Renewable Energy Centre (NaREC) in Blyth has a world-leading facility for testing turbine blades up to 70m in length. Further capability is needed for testing under extreme environmental conditions.

* Lack of dedicated blade materials R&D programme addressing both fundamental materials property issues as well as manufacturing technology for wind turbines.

* There is a need for a greater understanding of the fatigue behaviour and mechanical performance of large composite structures in a variety of service environments.

4.6 References

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Annex A

Non-Destructive Inspection (NDI)

With turbine components increasing in size, challenges exist in developing and adapting suitable NDI techniques for accurate defect detection. For example, a major disadvantage of sandwich blade construction is that manufacturing defects cannot readily be detected using conventional techniques. Rapid inspection is also an issue as blade size / volume of material increases. Visual inspection and tap testing have routinely been used but more accurate techniques are needed. The most promising techniques are X-ray, ultrasound and shearography. Specific challenges that need to be overcome include:

- Development of techniques that can detect defects located deep within sandwich constructions
- Improved sensitivity and reliability of NDI techniques when applied to composite materials to allow detectability limits and probabilities of detection to be defined

Structural Health Monitoring (SHM)

Effective structural health monitoring of wind turbine components is inhibited by accessibility, due to the large / complex component geometry and to the often remote in-service locations. Development is required into on-line, remote fibre optics, acoustic emission and accelerometer sensor systems. Blade failures are rare but many turbines and blades are still relatively young and yet failures have occurred. Long-term performance attracts considerable interest, especially when rapidly changing blade sizes result in frequent 'new' designs. In order to establish what critical performance indicators need to be measured/monitored, it will be necessary to establish a fuller understanding of parent material behaviour and likely in-service failure modes.

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5.0

Biomass technologies

Increased interest in development of renewable energy technologies has been encouraged by legislative measures in Europe to reduce CO_2 emissions from power generation in response to the potential threat of global warming.

Of the available technologies, biomass firing has a high priority because of the modest technological risk involved and the ready availability of waste biomass in many countries [1]. Biomass fuel can be supplied from a variety of sources, and in a variety of forms. Sources include waste biomass, either from agriculture/forestry operations (e.g. wheat straw) or from the green element of municipal or industrial waste and farmed biomass, 'energy crops' from land-based agriculture or from the sea. Biomass from the sea (seaweed) avoids the competition with food production for land and fresh water, but contains very high levels of contaminants restricting options for its use. Possible forms of biomass fuels are:

- as a solid fuel in either raw (as collected/harvested and dried) or semi-processed into pellets or some other more handleable form
- as a liquid or gaseous fuel [e.g. by using pyrolysis, gasification, anaerobic digestion, etc, with further processing]

5.1 UK Strengths and Weaknesses

UK has a growing industry in small-scale bioenergy systems for heat and power applications. However, Europe is some way ahead in deployment of these systems, particularly in countries where large quantities of waste biomass are available from the forestry sector (e.g. Finland), or where Government pressures/initiatives have encouraged early development. UK has established strengths in heat exchangers, gas turbines, etc., and its major energy companies are strongly represented in the global market for bioenergy systems.

Prior to such initiatives as the Non-Fossil Fuel Obligation and the Renewables Obligation, biomass technologies were primarily focused on heat applications, which continue to be an economically competitive niche market. Support measures have encouraged development of new heat and power options but few of the installed plants would maintain their status without continuing support.

Major research initiatives have been established in recent years, such as the Research Councils' Supergen and 'Towards a Sustainable Energy Economy' programmes. As a result, the UK has considerable strength and capability in biomass energy technology research.

5.0 Biomass technologies

5.2 Combustion and Gasification

Combustion of waste and farmed biomass has been practised for many years around the world, mostly for heat production, but more recently for the generation of electricity.

Highly efficient energy conversion from biomass has not been a priority where biomass was a waste product but is of increased importance where biomass is purchased as an energy crop. Efficiency is also important in large-scale power generation, where bioenergy has to compete with other fuels. In such cases, bioenergy system efficiencies have always fallen well below those of equivalent fossil-fired systems.

The limited efficiencies of biomass conversion systems has been due to reduced steam conditions enforced by severe fouling and corrosion problems experienced as a result of the high contaminant levels from many biomass fuels, which lead to reduced component lives. While coal plants aim for 650˚C/300bar steam and above, biomass plants are currently operating at less than 540˚C/100bar steam with efficiencies of typically less than 30%. However, substituting biomass for coal in co-fired advanced coal plants brings biomass together with high efficiency plant. Issues associated with co-firing are reviewed in the Fossil Energy Report.

In Denmark, government legislation has driven the introduction of ever more efficient plants. The most advanced straw-fired biomass plant operates at 540˚C/92bar with an electrical efficiency of 29%. Experience from boilers in Sweden firing 100% forest fuel indicates that conventional superheater steels last no longer than four years or 20,000 hours before they must be replaced because of corrosion damage. This leads to higher operating costs making biomass combustion plants uncompetitive with fossil plants, unless supported through subsidies or grants. Using waste biomass sources, such as demolition wood, improves overall plant economics but leads to even more severe corrosion problems. In addition to the impact of biomass fuels on operating costs, capital costs of biomass plants are usually higher than their fossil counterparts, due to more complex fuel feeding arrangements, fuel drying, gas cleaning, emissions monitoring requirements, etc.

In order to improve system efficiencies and economics of biomass plants, recent interest has focused on gasification systems. These include:

- Fixed or moving bed gasifiers (either updraft or downdraft) for small-scale use to:
- Circulating fluidised bed combined cycle systems, which take advantage of the higher efficiencies of gas turbines and advanced gas engines at medium-scale (up to 30MWe).

While different gasification options are possible [2], circulating fluidised bed gasifiers have been developed furthest because of their flexibility and suitability for the large quantities of biomass feedstocks. Both atmospheric pressure and pressurised schemes have been demonstrated using a small (4MWe) industrial gas turbine.

A variant of the TPS Termiska Processer AB circulating bed gasification system [3] from Sweden was the world's first 'commercial' biomass gasification plant. It was known as the ARBRE project and was developed at Eggborough, Yorkshire. Unfortunately this plant has now closed. The plant aimed to use coppiced willow and forestry residues in chipped form to produce 8MW of electricity with a cycle efficiency of ~31%. A generic flowsheet for the hot gas path of this plant through to the gas turbine is shown in Figure 1.

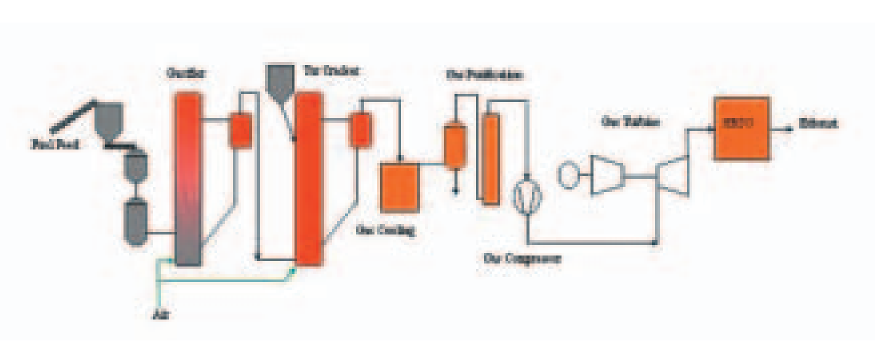


Fig. 1. Simplified flowsheet for the hot gas path of the ARBRE project

Fig.1 shows the complexity of the hot gas path in such systems. Even though fluidised bed gasifiers lead to moderate fuel gas tar levels, a high temperature cracker is still needed to reduce energy losses and limit the tar removal burden at the gas purification/scrubbing stage. Tars would otherwise cause substantial problems in the gas compressor. Ammonia levels in the fuel gas are a further concern as they lead to excessive NO_X levels in the gas turbine exhaust and exceed the allowable emissions limits. Scrubbers can reduce levels of ammonia in the fuel gas and post-combustion catalytic systems can be used to reduce NO_X emissions.

In a pressurised system, such as that in the Varnamo project [4], there is no requirement for a fuel gas compressor (see Fig. 2). Hence tars can be kept hot in the vapour phase provided they do not exceed the gas turbine entry limits and do not cause blinding problems in the hot gas filter. Using high pressure and a hot gas cleaning approach reduces complexity and raises cycle efficiency. The measured efficiency in the Varnamo project was 32% but up to 38% could be expected from application of the latest gas and steam turbine technology. This scheme used a variety of biomass fuels to demonstrate its flexibility and produced 5MW of electricity and 9MW of heat for district heating. Figure 2 shows the hot gas path through to the gas turbine.

While gasification leads to higher efficiencies, it is more complex and expensive to build. It is also susceptible to contamination problems, which have led to operational restrictions in biomass combustion plant. The next section of this report reviews the possible effects of contaminants in biomass gasification systems with particular emphasis on the durability of the gas turbine and the implications this may have on gas cleaning.

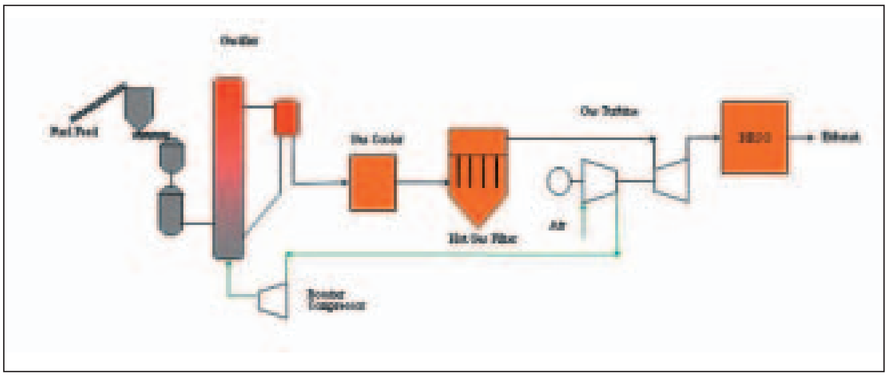


Fig. 2. Flowsheet for the hot gas path of the Varnamo project

5.0 Biomass technologies

5.3 Biomass Characteristics

Like coal, biomass contains a wide range of elements that may react to form potentially harmful deposits in gasification systems and gas turbines.

The 'mix' of elements in fuel gases produced in gasification is highly dependent on the biomass fuel composition. Before biomass firing can be used with any confidence in gasification systems, it is necessary to investigate the effects of deposits and gas environments on gas turbine components.

From such information, fuel specifications for biomass-fired gas turbines can be derived, thereby ensuring adequate component lives and the possibly of using state-of-the-art gas turbines.

To investigate the effects of contaminants in the hot gas path of biomass gasification plants it is necessary to compare contaminant levels in biomass fuels with those in coal-fired combined cycle gasification systems, for which there is considerable experience. Although extensive composition information has been gathered on potential European biomass fuels [5] few analyses have been carried out for all minor and trace metal species. Average data for pinewood, wheat straw, a range of grasses, sewage sludge and peat has been compared with coal and is given in Tables 1 & 2. It should be noted that there are significant differences in the errors associated with each of the values due to inherent fuel variations, variable sample sizes and different analytical methods.

Table 1 illustrates the major differences between biomass fuels and coal. Biofuels have:

- Higher moisture content and therefore use some heat for drying
- Lower ash (except sewage sludge)
- Lower sulphur (S) levels and similar or higher chlorine (Cl) levels

In addition, biofuels often give higher NO_X & ammonia (NH_3) levels in combustion and gasification systems respectively compared with fossil fuel counterparts.

Table 2 presents average ash compositions derived using standard ash analysis techniques. Note the differences in ash contents from Table 1. It is generally true that fast growing biomass fuels contain higher alkali metals, in particular potassium. Although the method used to generate ash for analysis was designed for coal combustion, the general findings suggest that fouling and corrosion problems should be expected in biomass systems.

Table 1. Average analyses of biomass and fossil fuels

	Wood	**Wheat Straw**	**'Grass'**	**Sewage Sludge**	**Coal**
Moisture (wt%)	20.7	10.7	14.9	19.5	8.2
Ash (wt%)	1.7	5.9	5.2	43.4	12.7
S (wt%)	0.2	0.1	0.2	1.0	1.7
Cl (wt%)	0.1	0.8	0.2	0.1	0.2
LHV, MJ/kg	18.6	17.3	18.3	10.7	26.2

Table 2. Ash analyses of biomass and fossil fuels

	Al_2O_3	SiO_2	Na_2O	K_2O	MgO	CaO	Fe_2O_3	P_2O_5	SO_3	TiO_2
Wood	5.5	24.3	1.7	9.3	4.5	34.5	3.6	5.6	5.5	0.4
Wheat Straw	1.8	49.6	3.7	22.2	2.9	6.0	1.0	2.6	3.3	0.1
Grass	2.8	59.5	0.7	15.3	3.4	7.4	1.6	8.6	1.4	0.2
Sewage Sludge	15.0	34.6	1.0	1.4	3.1	17.3	10.6	10.0	1.3	1.0
Coal	18.1	40.8	3.5	2.4	3.8	10.3	12.3	6.2	6.2	0.8

There is a tendency for higher chlorine/lower sulphur levels to favour formation of chlorides over sulphates, while the lower ash contents provide less dilution of any deposits formed on plant components.

It is thought that the high potassium content combined with chlorine is also responsible for the formation of low melting temperature compounds during combustion. The low sulphur content in many biomass fuels is another contributing factor. These low melting point ash constituents induce widespread fouling and severe corrosion problems.

In gasification systems there are several possible pathways that minor and trace elements, such as sodium, potassium and heavy metals, can take, thereby influencing the amount that will reach the gas turbine or engine. Options include:

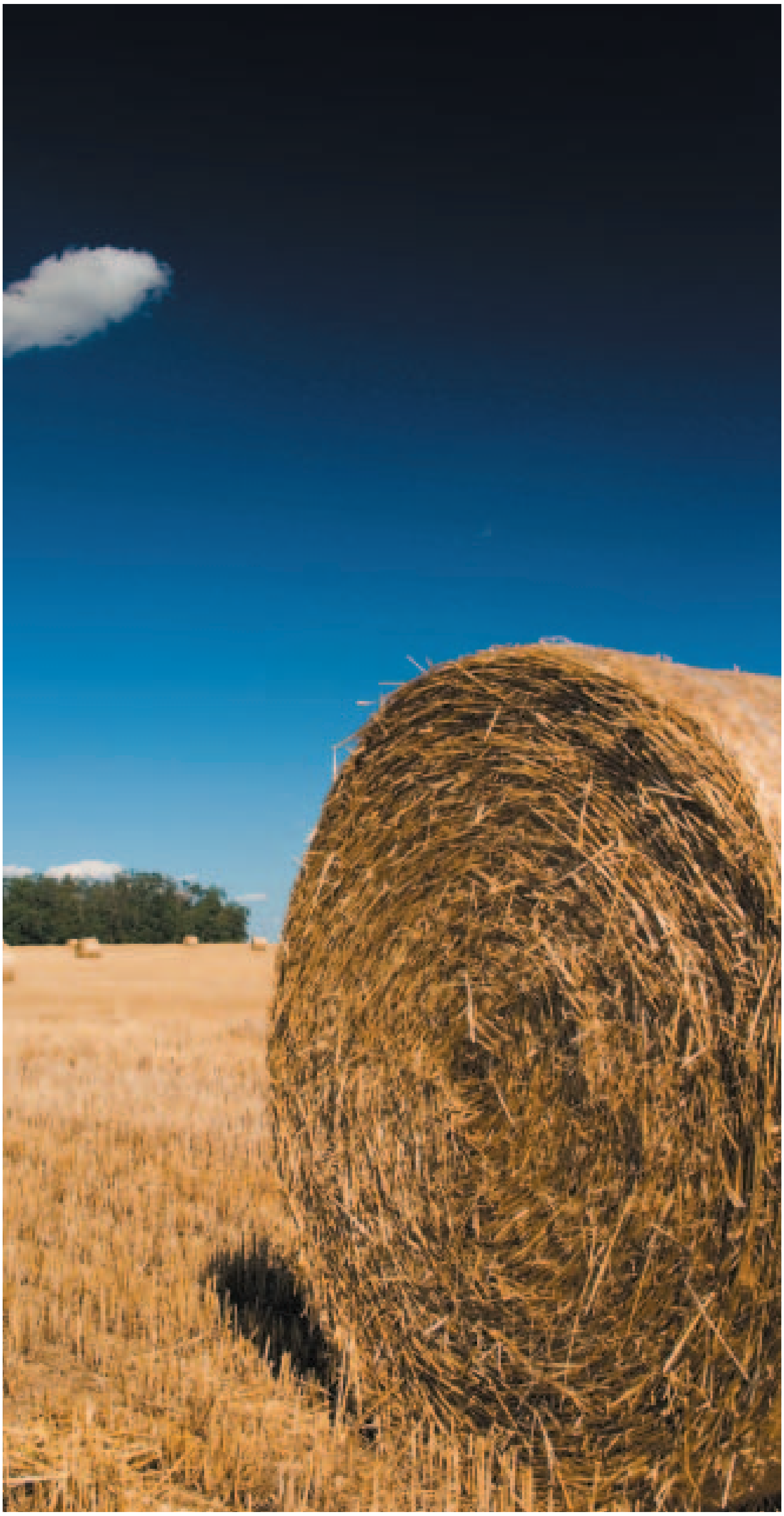
- No response to the gasification process so the minor/trace elements will exit with the ash/char/slag, to
- Formation of vapour species that can pass through the whole hot gas path and thereby will be emitted from the process

In between these two extremes it is possible for reactions to take place that lead to:

- Condensed particles or vapour species that can condense onto entrained particles/plant components within the hot gas path [depending on specific operating conditions]

The fate of the various trace elements is element-specific. It is also influenced by:

- Relative and absolute levels of other elements present in the fuels [e.g. S & Cl]
- The sorbents or catalysts used
- The material compositions of hot gas path components.



5.0 Biomass technologies

5.4 Materials Issues

In biomass-based combustion systems the key materials challenges are increased levels of fouling and corrosion, which then limit operating steam temperatures. The aim is to be 'fuel flexible', thereby taking advantage of cheap local sources of biomass from either waste or farmed sources.

Such versatility requires improved durability of heat exchanger materials or biomass pre-treatments to remove the aggressive contaminants, or the use of additives to reduce fouling/corrosion. For example use of sulphur-bearing additives can reduce chlorine levels in deposits. A combination of these options is likely to deliver 'best practice'. It is also possible to use additives to reduce fouling/corrosion in certain circumstances.

Even the best available materials, such as Alloy 625, have problems meeting power plant life requirements. Coatings have been investigated at length but it is difficult to achieve both effective corrosion resistance in the aggressive conditions and economic viability. Further research is a priority for both evaporative and superheating duties.

Major materials issues can be avoided in initial gasification-based systems, for both power generation and gaseous/liquid fuel production, by careful process and design choices. The need to extract heat energy from the hot gas is a lower requirement in biomass gasification than in much larger, coal-based integrated gasification combined cycle power plants. However, future biomass systems may require greater heat extraction [see the Gasification review for details] and so could encounter significant materials challenges. Cleaning the gas to safeguard downstream components and reduce subsequent emissions are however critical issues.

Optimum performance of the gas turbine is vital in all biomass combined cycle systems to ensure overall plant efficiency and economic viability. Hot corrosion and/or erosion are likely to be life limiting for high temperature components such as gas turbine vanes and blades in the hot gas path, rather than creep and fatigue processes that limit life in natural gas systems. This is due to higher contaminant levels in biomass systems. As a result, process choices and performance of gas cleaning components are dominant factors.

Industrial gas turbines have been developed to use a wide variety of fuels - from natural gas to sour gases and heavy fuel oils. Degradation of materials in such systems has been widely investigated over the past 40 years [6, 7]. Fuel gases derived from biomass have the potential to cause both erosion and corrosion damage to gas turbine hot gas path components. Fuel derived particles can cause both erosion damage and deposition depending on the particle size and composition, as well as aerofoil design and operating conditions. Corrosion can result from the combined effects of gaseous species (e.g. SO_X and HCl) and deposits can form by condensation from the vapour phase (e.g. alkalis and other trace metal species) and/or from particle impact and sticking.

Corrosion damage is highly dependent on the local component environments. The metal vapour species of most concern were alkalis [mainly sodium] in gas turbines fired on clean fuels or vanadium from heavy fuel oils. In biomass fired systems the levels of SO_X and HCl can be similar or higher than those from a coal gasifier (see Table 1). Also, the fuel gas may contain significant levels of alkali metals [in particular potassium] and heavy metals [e.g. lead and zinc (8)] depending on the biomass type (Table 2) and the effectiveness of the gas cleaning approach. If a water or chemical scrubber is included [as in the ARBRE scheme for ammonia removal] levels of these contaminants will be significantly reduced whereas a hot/dry cleaning approach can lead to higher levels, depending on the operating temperature of the filter.

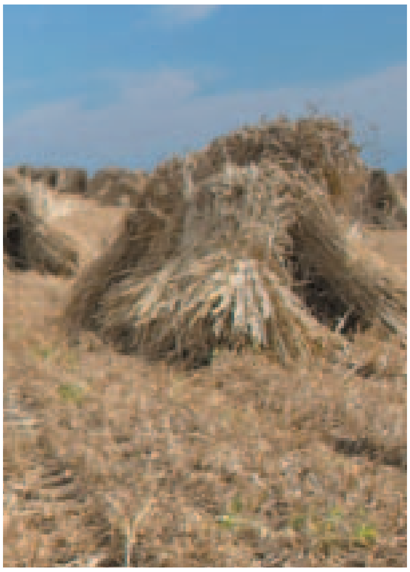
Care is required in the control of trace alkali and other contaminants because of their potential to give excessive corrosion damage to hot gas path components in a gas turbine using a biomass-derived fuel gas [9]. The exact level of damage that can be tolerated by the turbine depends on specific process and operating parameters [e.g. blade temperatures, materials, repair/replacement strategy etc.] as well as economic factors [10-15]. It may be possible to optimise materials selection and operating conditions in combination with a maintenance strategy that allows higher than currently specified contaminant levels, instead of using a high cost elaborate gas cleaning system. One research option is to continue development of improved protective coatings that allow biomass systems to take advantage of advanced high efficiency gas engines and turbines, thus assisting economic viability.

For gaseous and liquid fuels prepared from biomass, whether for heat, power or transport, the issues revolve around the levels of contaminants remaining in the fuels. Similar materials issues to those described above can arise.

5.5 Conclusions

Materials challenges arising from use of biomass in energy processes have been evident for many years. Remaining impediments to increased deployment of these relatively low risk, renewable energy options include:

- Improved alloys and coatings for evaporator and superheater heat exchangers and gas turbine/gas engine hot gas path duties
- Life prediction modelling for heat exchangers to optimise maintenance and repair procedures
- Monitoring of corrosion/contaminants in order to provide early warning of problems
- Improved repair/refurbishment procedures for heat exchangers and gas turbine parts



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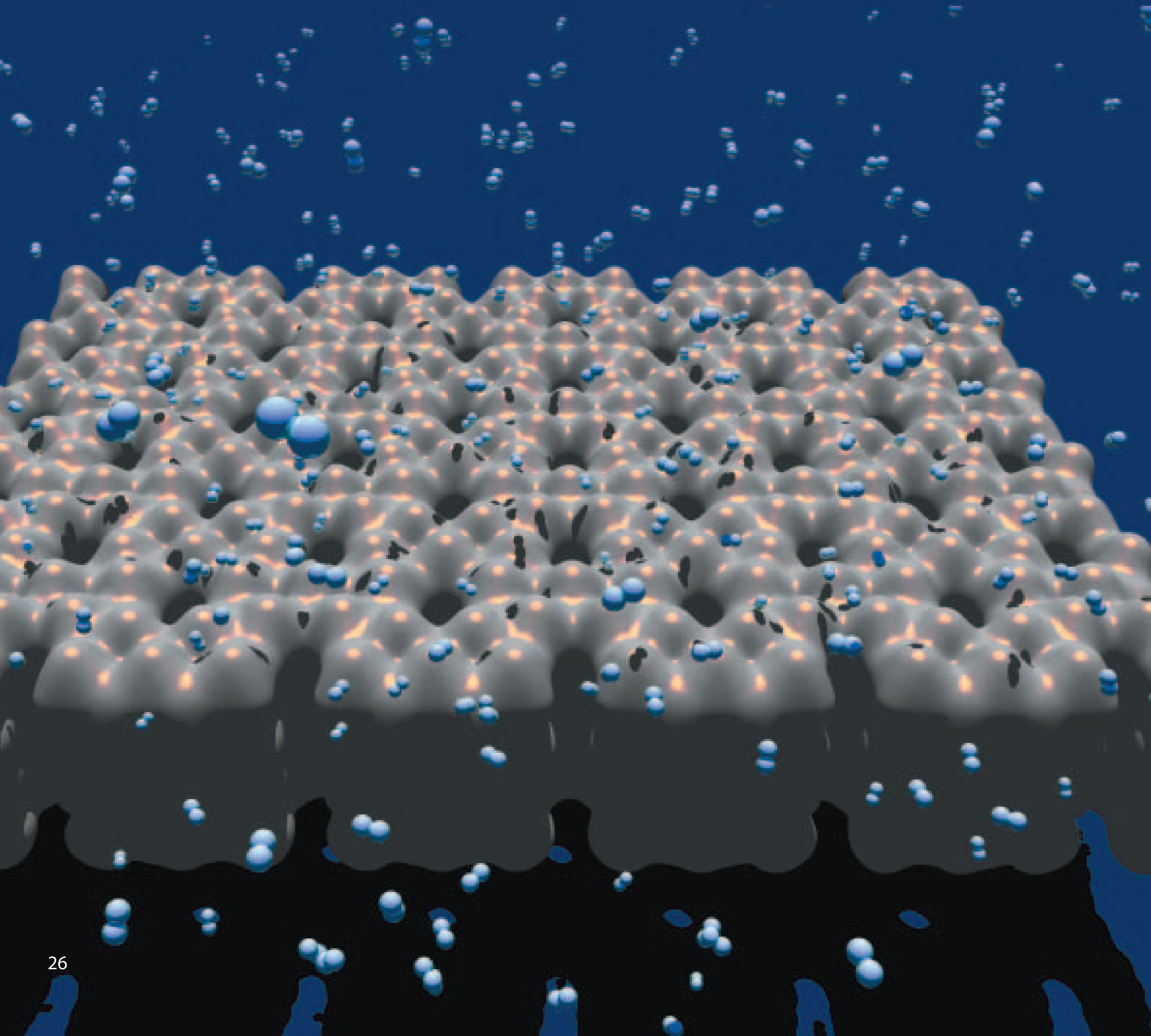


6.0

Hydrogen

The environmental and energy security benefits of moving towards a hydrogen economy have been widely discussed and accepted in Europe, Japan and US.

The principal drivers behind a sustainable energy vision based on a hydrogen-oriented energy economy are:

- Reducing greenhouse gas emissions
- Improving our security of energy supply
- Strengthening the UK economy
- Improving local urban air quality.

Unlike fossil fuels, hydrogen is not a primary energy source. Instead it is an “energy carrier” which is first produced from another energy source and then transported for future use, where its latent/stored chemical energy can be utilized. Fundamentally, hydrogen resembles electricity as a carrier of energy/secondary energy source rather than a ‘prime mover’.

Hydrogen can be obtained from a wide variety of both renewable and sustainable resources that include hydro, nuclear, wind, wave, solar, biomass and geothermal as well as non-renewable resources, such as coal and natural gas. Hydrogen can be utilized in high-efficiency electrical power-generation systems, most notably in fuel cells for both vehicular transportation and distributed electricity generation. Fuel cells convert hydrogen (or a hydrogen-rich fuel) and an oxidant (usually pure oxygen or oxygen from the air) directly into electricity via an electrochemical process. This close synergy between hydrogen and fuel cells is a key facet of any future UK energy scenario. Hydrogen technologies are also set to play a key role in large-scale power generation, with pre-combustion carbon capture and storage technologies relying on initial conversion of fossil fuel into a hydrogen-rich synthesis gas stream. Hydrogen and CO_2 are separated by physical or chemical methods before the hydrogen is burnt in turbines or, in future scenarios, efficiently converted to electricity in solid oxide fuel cells.

Any transition from a carbon-based/fossil-fuel energy system to a hydrogen-based economy involves overcoming significant scientific, technological and socio-economic barriers before ultimate implementation of hydrogen as the clean energy source of the future. If these difficulties are overcome, energy supply and transformation could be developed along two primary energy distribution networks - the electricity network and the hydrogen network. Within such a scenario, oil may not be the dominant energy provider, but will be utilised for the synthesis of key chemical products (Figure 1).

Research and development priorities can be divided into three over-arching clusters centred on hydrogen production, hydrogen storage and hydrogen utilization. In all of these areas, materials research is a major factor in advancing a UK Hydrogen Energy Future. Particular emphasis is placed here on the importance of building a strong base of fundamental research activities in priority areas. The importance of crosscutting activities is also emphasised, whereby progress in one area will significantly impact on other areas, thereby accelerating progress.

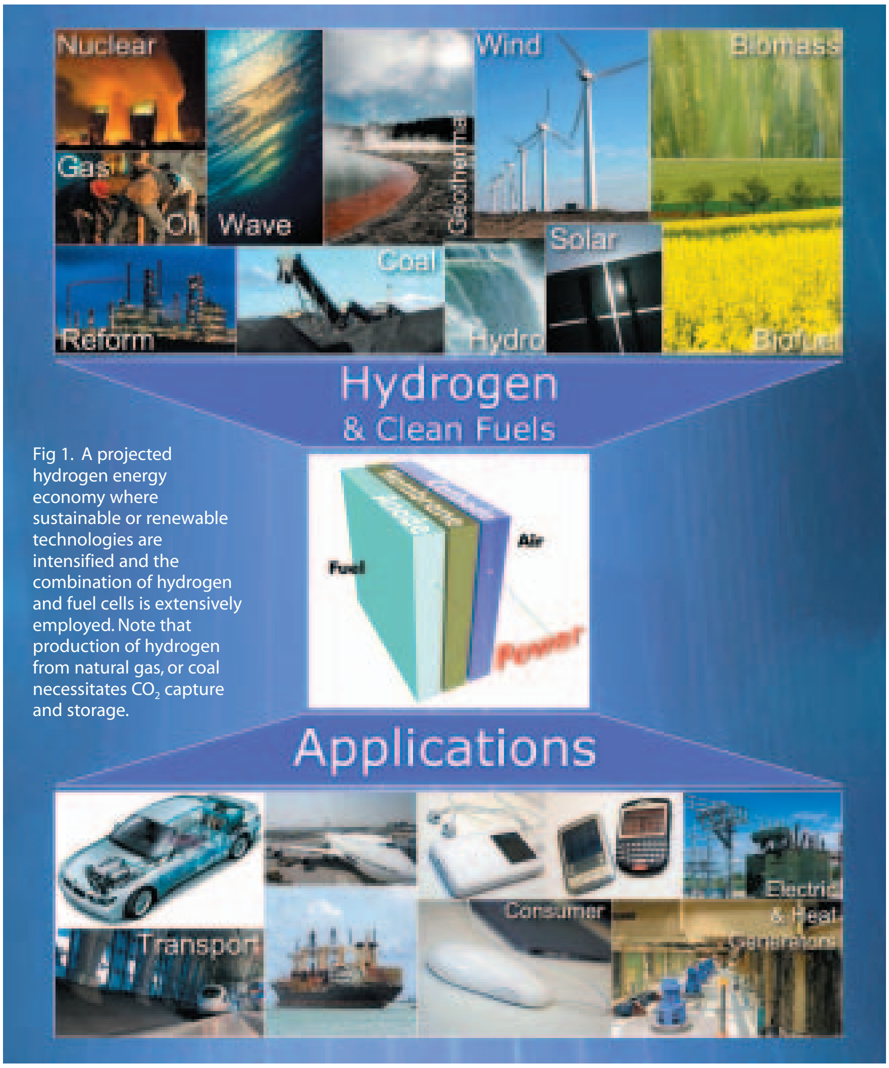


Fig 1. A projected hydrogen energy economy where sustainable or renewable technologies are intensified and the combination of hydrogen and fuel cells is extensively employed. Note that production of hydrogen from natural gas, or coal necessitates CO_2 capture and storage.

6.0

Hydrogen

6.1 Priority Research Areas for Hydrogen Energy

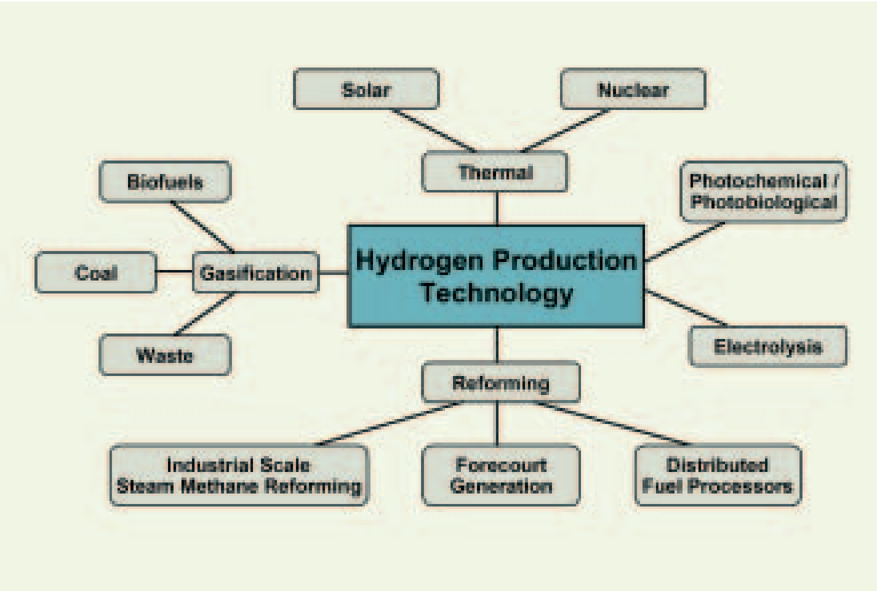
Hydrogen Production: Routes to Hydrogen

Even though hydrogen is highly abundant, it is invariably bound-up with other elements in chemical compounds. Some 95% of hydrogen is currently produced from fossil fuels. Hydrogen production (Fig. 1) is the key to developing a hydrogen economy and ultimately to sustainable or renewable energy routes.

The UK has a world leading position in production of hydrogen from hydrocarbon feedstocks, with extensive catalysis, chemical and process engineering expertise. It is vital that the UK maintains and extends this position by expanding this expertise into new areas, such as large-scale power generation and distributed hydrogen technologies as well as investing in next-generation hydrogen technologies centred around renewable energy sources.

Bearing in mind regional variations, a broad portfolio of hydrogen production routes are now envisaged. A representation of various process technologies is shown in Figure 2.

Fig 2. Possible hydrogen production pathways.



In the short and medium term, production options for hydrogen are still based on reforming of natural gas and coal and on distributed hydrogen production from electrolysis of water. Larger centralised production plants are likely to be introduced at a later stage, based on fossil fuels, again with CO2 capture and storage, and biomass. An increasing emphasis will be placed on hydrogen from solar energy (solar hydrogen) and on utilisation of thermo-chemical energy for massive-scale hydrogen production (via nuclear energy or solar energy).

Hydrogen from Fossil Fuels: Reforming and gasification

90% of hydrogen is currently produced by steam methane reforming. This “merchant hydrogen” is used mainly for ammonia & methanol production, as well as refinery upgrading.

Distributed-scale fuel processors generate a hydrogen-rich reformate feed locally for fuel cells by reacting readily available hydrocarbons such as natural gas, LPG and gasoline, with water (Steam Reforming), air (Partial Oxidation) or a combination of the two (Auto-thermal Reforming).

Materials challenges for next-generation hydrogen production catalysts at both industrial and distributed scales arise from:

- The need to cope with heavier hydrocarbon fuels that are intrinsically more difficult to process
- Use of dirtier feedstocks (e.g. biomass and coal), which require pre- and post-processing to remove impurities, particularly sulphur, mercury (Hg) and arsenic (As)
- The harsher process environment of small-scale hydrogen generation systems, which demand catalysts that are highly active and resistant to a wider range of operating conditions, including repeated cycles, reduced steam ratios and oxidative start-ups/shut-downs.

Hydrogen production and processing catalysts need to be tailored to the specific application (Figure 3). Large scale processes use pelleted base metal catalysts (e.g. - nickel-based for reforming, FeCr or copper-based for water gas shift), whereas distributed systems can use supported precious metal catalysts that are coated onto ceramic or metallic substrates in a manner resembling automotive catalytic converters. The higher cost of these catalysts can be offset by their more effective intrinsic performance and robustness.

Developing the next generation of catalysts and adsorbents will require basic research into nanoscale synthesis, molecular modelling, kinetic and mechanistic reaction studies. Advanced analytical techniques are also needed to rapidly characterise catalysts and their activities under realistic working conditions. This will involve characterisation of structure and dynamics of active catalyst sites at the atomic level.

Integration of catalysts into efficient and compact hydrogen generation systems will require research into advanced reactor concepts, such as auto-thermal reforming, micro-channel reactors and mini-channel reactors. Many of these techniques place stringent demands on the materials of construction and associated manufacturing methods.

Hydrogen Purification

Fuel cells can directly use the hydrogen rich reformate gas stream that comes from a fuel processor. However, such streams contain trace hydrocarbons, sulphur compounds and carbon monoxide that can be detrimental to the performance or lifetime of the fuel cell. The amount of gas clean-up necessary depends on the fuel cell type. High temperature fuel cells requiring less pre-processing than low temperature fuel cells, which may require several stages of water gas shift, and selective oxidation to remove CO from the feed.

Advanced catalyst and adsorbent materials need to be developed that are appropriate to the fuel cell application. For example, deep desulphurisation of liquid hydrocarbon feeds would allow for additional fuel flexibility, whereas removal of sulphur from a high temperature reducing stream could offer significant system benefits. Such feedstocks could also impact on larger-scale hydrogen production flowsheets, where catalysts and adsorbents tailored to operate in a particular operating envelope could improve efficiency and reduce capital costs by simplifying heat management.

Where hydrogen is stored as a fuel source for fuel cells, it needs to be further purified to remove all diluents, particularly CO_2. Technologies for achieving this at an industrial scale are well established and include pressure swing adsorption and amine scrubbing. However, fuels such as coal, waste and biofuels bring additional materials challenges as the range and level of contaminants is correspondingly higher.

At the distributed scale, there is significant scope to develop advanced gas separation techniques, particularly those based around membranes and small scale PSA. Thin film Pd-alloy membranes are of particular interest as they have a high selectivity to hydrogen. Membrane technologies have the potential to be applied to large-scale hydrogen plants, particularly those with associated carbon capture and storage (CCS), where CO_2 retentate would remain at pressure. Membrane systems of interest include porous materials (e.g. - carbons, zeolites, and silicas), as well as impermeable metallic systems (e.g. vanadium and palladium films). Materials scale-up issues, as with all membrane types, are significant. Chemical looping is an example of another advanced concept for H_2/CO_2 separation. At large scale this requires significant materials R&D.

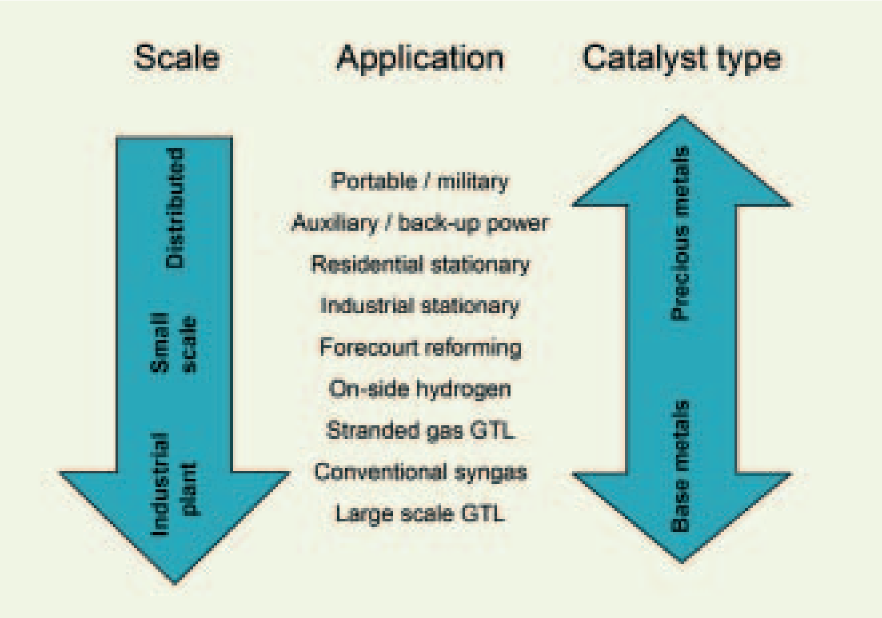


Fig 3. The use of a variety of catalysts will be a major feature of hydrogen production from small-to-large scale applications.

6.0

Hydrogen

Hydrogen from Electrolysis

Water electrolysers have great potential to harness renewable energy resources, such as wind and solar to create hydrogen as the energy carrier.

Electrolysers are electrochemical devices which can use electrical energy to split water into hydrogen and oxygen. In electrolysis cells the hydrogen and oxygen are produced as pure gases. Where a solid polymer is used as electrolyte, this technology is called Proton Exchange Membrane (PEM) electrolysis.

PEM electrolysers offer the possibility of low-cost hydrogen and oxygen generation in small, highly efficient units that are suitable for distributed, as well as centralised, operations.

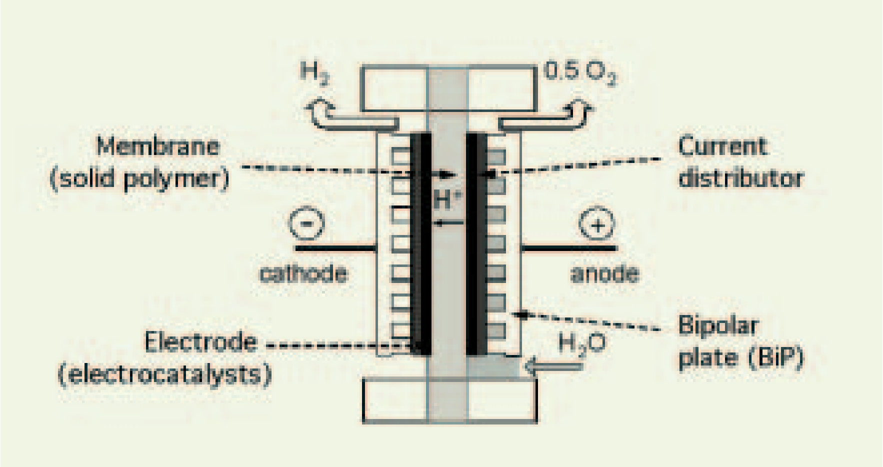
There are many similarities between the materials challenges facing PEM electrolysers and PEM fuel cells, [see Section 7], particularly the development of lower cost components (catalysts, electrodes, membrane, bipolar plates) which demonstrate higher performance and improved durability and can be integrated into mass manufacturable processes.

Hydrogen from Solar Energy

For solar, photovoltaic, photo-electrochemical or photo-catalytic hydrogen production to become economically viable, it will be necessary to achieve both a high level of efficiency and dramatically reduce the cost of the entire process. The need to create a “disruptive technology” here is great. Challenges include:

- Development of new electronic ‘band-gap engineered’ or molecular-level designed materials and chemical processes that are integrated for fabricating inexpensive solar cells or photo-catalysts.
- Development of a fundamental understanding of the mechanism of both electron and hole diffusion and transport in solids and across interfaces to liquids. For example, the factors that influence the mobility of charge carriers in inorganic, organic and hybrid systems need to be understood as well as the role played by surface states, grain boundaries etc in dictating the efficiency of PV and photo-electrochemical cells.
- Developing synthetic routes to inorganic/organic/polymer hybrid materials with controlled structure / function in tandem with consideration of mechanisms [as above]. Synthesis of defect-free nanoparticles with control of shape, size and interfacial chemistry is also needed combined with an understanding of electron and hole transport and conduction in multi-component and multilayer photo-catalytic materials.
- In situ characterisation of complex, multi-component chemical systems in the development of efficient solar cells and photo-catalysts for hydrogen production. The aim is a molecular-level understanding of both structure and function for materials optimisation.
- Theory and modelling of complex photo-systems (e.g. femtosecond dynamics of charge carriers and their recombination processes).
- An understanding and control of the various processes leading to degradation of solar cells, most notably dye-sensitised and nanoparticle systems in order to achieve a minimum of 10 years of useful life.
- Enhanced understanding of molecular and heterogeneous catalysts, particularly for the oxidation of water to oxygen. Photo-catalytic studies of direct water splitting and CO_2 reduction with complex redox catalysts are needed for next-generation photo-catalysts.
- Exploration of hydrogen production involving electron and ion transfer at catalyst/electrolyte interfaces.

Fig 4. Schematic diagram of Proton Exchange Membrane electrolysis.



Hydrogen from Thermal Energy

If the hydrogen economy is to come to fruition, novel and thermodynamically efficient routes must be discovered to manufacture hydrogen - from a sustainable non-carbon feedstock - at an industrial scale. The obvious feedstock is water. Thermodynamic studies have already demonstrated the significant potential for thermochemical cycles to deliver mass-scale manufacture of hydrogen.

A large number of thermochemical cycle systems exist for water splitting. Materials needs are urgent because of the requirement to operate in an aggressive chemical environment at elevated temperatures. Thermochemical cycles using heat from either high-temperature solar or nuclear sources are possible.

Key high-level materials development will include:

- Materials that are robust, cost effective and compatible with extremes of both chemical and thermal environments.
- Materials for improved separation processes that function at high temperatures. Such processes include separation of SO_2 and O_2 from SO_3 and separation of H_2O and HI from $H_2O/I_2/HI$ mixtures, and renewal of H_2.
- Understanding the fundamental electrochemistry and materials chemistry leading to hydrogen and oxygen generation for improved designs of electrolyser and electrode materials.
- Thermodynamic modelling aimed at estimating the achievable efficiency for all candidate thermochemical cycles. This will allow production of robust, experimentally-validated process models of the Hybrid Sulphur Process (HyS) [a variant of the so-called Westinghouse thermochemical cycle]
- Improved next-generation catalysts for these high temperature processes, which would allow thermochemical cycles to operate at lower maximum temperature, thereby offering more flexibility in reactor design and optimisation of cycles.
- Production of alternative energy carriers beyond hydrogen, such as ammonia (NH_3) as a chemical product synthesised using heat obtained from thermochemical processes from both fission and fusion reactors.

6.0 Hydrogen

6.3 Hydrogen Storage

Main Requirements for Hydrogen Storage

Developing effective hydrogen storage, particularly for transportation, is a pivotal challenge for basic research and a key factor in enabling ultimate success of the hydrogen economy.

Hydrogen storage onboard vehicles are considered central to achieving market success for fuel cell vehicles.

The necessary operating requirements for effective hydrogen storage for transportation include the following:

- Appropriate thermodynamics (i.e. favourable enthalpies of hydrogen absorption and desorption)
- Fast kinetics (quick update and release)
- High storage capacity. This capacity is determined by usage, e.g. transportation or stationary applications.
- Effective heat transfer
- High gravimetric and volumetric densities (lightweight and conserving space)
- Long cycle lifetime for hydrogen absorption / desorption
- High mechanical strength and durability
- Safety under normal use and acceptable risk under abnormal conditions.

The major challenge is to store enough hydrogen on board a vehicle for an equivalent driving range of some 300 miles whilst meeting performance (weight, volume, kinetics etc), safety and cost requirements, without compromising passenger or cargo space.

Specific performance targets for hydrogen fuelled transportation are given in Table 1.

Recent systems studies suggest that the hydrogen storage system should have a specific energy of 3.0 kWh kg^{-1} and a cost of \$ 2 kWh^{-1} to meet the Table I goals. No current hydrogen storage technology meets these targets. Figure 5 shows the current status of hydrogen storage systems in terms of cost and volumetric and gravimetric energy capacities. It is recognised worldwide that new materials for hydrogen storage represent an area where a potential step-change in performance might be achievable. Current methods of hydrogen storage are described below, together with fundamental materials research issues that are needed to achieve hydrogen storage goals.

A representation of the range of volumetric and gravimetric densities for storage systems is shown in Figure 6.

Furthermore, whilst economic and energy dense storage systems are required for the hydrogen fuelled vehicles, the requirements for hydrogen distribution should not be overlooked. Performance limitations and through life economic factors must be clearly understood for hydrogen tankers, pipelines and large underground / above ground storage facilities.

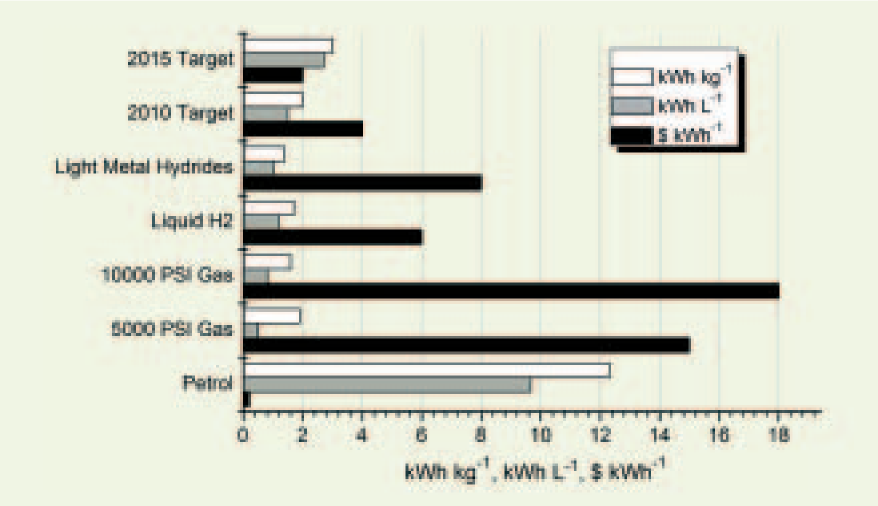
Gaseous and Liquid Hydrogen Storage

The most common and mature storage technology is high pressure containment in steel tanks, although light-weight composite tanks, designed to operate at very high pressures are becoming more and

Table 1. Hydrogen storage system targets (US Department of Energy).

Targeted factor	2010	2015
Specific energy (MJ/kg)	7.2	10.8
Hydrogen (wt%)	6.0	9.0
Energy density (MJ/kg)	5.4	9.72
Delivery pressure (bar)	2.5	2.5
Operating temperature	-20/50	-20/50
Absorption/desorption cycle lifetime	1000	1500
Flow rate (g H_2/s)	4	5
System cost (\$/kg/system)	6	3
Refuelling rate (kg H_2/min)	1.5	2.0

Fig 5. The status of current hydrogen storage systems in terms of cost (kWh^{-1}), gravimetric (kWh_ kg^{-1}) and volumetric (kWh L^{-1}) densities. *[Adapted from S.G. Chalk and J.F. Miller, J. Power Sources, 2006, vol. 159, p. 73.]*



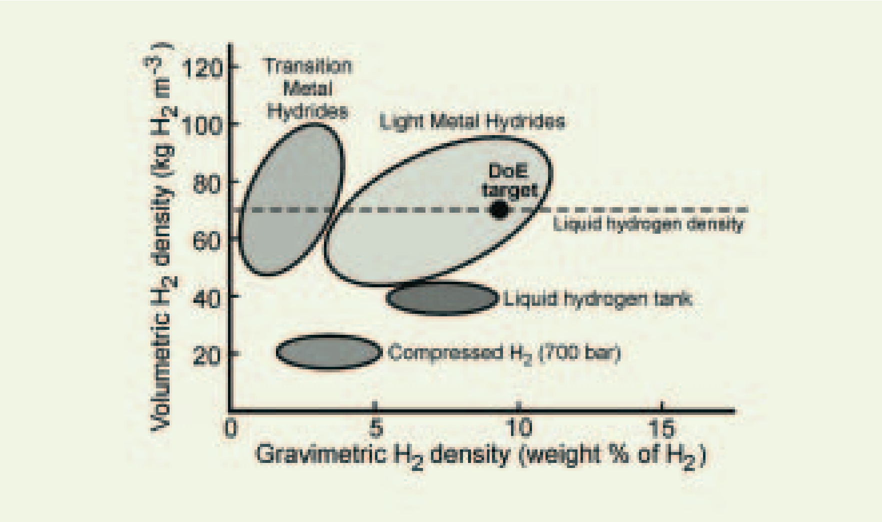


Fig 6. Gravimetric and volumetric densities of various hydrogen storage options (including weight and volume of the storage container). 'DoE target' represents the US Department of Energy target for 2015 set for an 'ideal' hydrogen storage material.

more common. Although this technology advances at pace, the long-term effect of hydrogen on the materials under cyclic or cold conditions is still not fully understood. Principal research needs for improved compressed gas storage centre on the development of new container materials that are strong, reliable and low in cost. The performance of materials in high pressure gaseous and liquid hydrogen is also relevant to valves, regulators, and other parts of storage and handling systems. Materials research areas can therefore be identified specifically as:

- Research on material embrittlement in high pressure gaseous hydrogen, centred on the atomic-scale mechanisms responsible for materials failure.
- Development of lower-cost storage and construction materials (notably low cost stainless steels and carbon fibres).
- Research on fatigue performance (particularly of welds) in high pressure gaseous hydrogen
- Development of 'hybrid approaches'; for example, using high pressure tanks which also include conventional metal hydride stores (e.g. $TiVH_{1.5}$) to reduce operating pressures.

Storage of hydrogen in cryogenic containers offers a significant advantage, since greater quantities of hydrogen can be stored in a given volume as a liquid than can be stored in gaseous form. I.e. liquid hydrogen has a much better energy density than pressurised gas options. BMW have developed a hydrogen-fuel-cell vehicle with onboard liquid hydrogen storage. A major drawback is the large quantity of energy required for hydrogen liquefaction - presently about one-third of the energy value of the hydrogen stored. Similarly, loss of hydrogen through evaporation is an issue, although quite major advances have taken place in recent years in insulation technology.

Basic research issues related to liquid hydrogen storage include:

- Discovery of new lightweight, low volume and low cost materials that have very low heat transfer characteristics.
- Development of systems and materials that automatically capture hydrogen gas boil-off. For example, use of metal hydrides / new materials for hydrogen capture and assistance in subsequent re-liquefaction of hydrogen.

6.0

Hydrogen

Transition Metal Hydrides

Many transition metals and their alloys can store hydrogen interstitially in their crystal structure, forming hydrides (e.g. $LaNi_5H_6$, $FeTiH_{1.7}$, VH_2 etc). Though the hydrogen volumetric density in some of these materials is higher than that of liquid hydrogen (Figure 6), the weight of the materials is impractical for onboard storage of hydrogen in vehicles. However, some transition metal hydrides are widely used as the hydrogen-storage electrodes in nickel hydride rechargeable batteries and could find use in a variety of stationary applications.

Apart from rather modest hydrogen storage capacity (around 1-3 wt%) and high cost, transition metal hydrides have a number of highly attractive features such as:

- low enthalpies for hydride formation
- good reversibility and cyclability of hydrogen adsorption / desorption
- the possibility to tune the hydrogen decomposition temperature by alloying.

Another important benefit of these materials is that they provide extremely pure hydrogen, therefore avoiding the cumulative build-up of impurities that could degrade the performance of Proton Exchange Membrane (PEM) fuel cells.

Basic materials research issues related to transition metal hydrides include:

- Understanding the effect of incorporated hydrogen on the electronic structure of the host lattice and the dynamics and energetics of hydrogen and its interaction with lattice defects in transition metal hydrides
- Development of new transition metal hydrides optimised for use in hybrid high-pressure hydrogen tanks
- Cost reduction and improvement in gravimetric hydrogen density whilst still operating at low temperatures (40-100˚C) and pressures (4-10 bar).

Light Metal Hydrides

Storage of hydrogen in light metal hydrides offers a range of possibilities to meet transportation requirements. Several classes of light metal hydrides have been studied worldwide including non-interstitial metal hydrides (e.g. MgH_2), alanates (e.g. NaAlH4), borohydrides (e.g. $LiBH_4$), amides (e.g. $LiNH_2$) and related materials/destabilised chemical systems. At present no single material investigated exhibits all the necessary properties.

Research emphasis has focused on meeting volumetric and gravimetric targets but two other key targets listed in Table 1 are fill time for hydrogen storage and the kinetics of hydrogen update/release. System fill time is strongly dependent upon the hydride formation enthalpy and the efficiency of the thermal management system. For example, in order to fill a tank with 4kg of hydrogen in 5 minutes a material with a heat of hydrogen adsorption of 30 kJ/mol will generate 200 kW of heat. To meet the power demands of a fuel cell vehicle US Department of Energy set a 2015 hydrogen flow rate target of 5g/s, which is equivalent to 50 litres of hydrogen /second. Ideally, this hydrogen release rate should be achieved at around 100°C to utilise waste heat from the fuel cells to desorb hydrogen, while a hydrogen storage material should still hold hydrogen at ambient temperatures and pressures of less than 10 bar.

Breakthroughs in solid state hydrogen storage will require revolutionary new materials to meet the hydrogen storage requirements. Material research priorities should include:

- A fundamental understanding of the physical and chemical properties of light metal hydrides, including crystal structure, homogeneity ranges, thermodynamics and kinetics of hydrogenation-dehydrogenation processes and electronic structure.
- An atomic- and molecular-level understanding of the physical and chemical processes involved in hydrogen storage and release.
- Understanding the critical role of dopants and the mechanisms of destabilisation reactions in altering the nature of hydrogen bonding and achieving reasonable kinetics and reversibility of complex hydrides at temperatures of 80-150K.
- New cheap synthetic processing routes to avoid lengthy and expensive solvent-based synthesis and regeneration of novel light metal complex hydrides.
- Studies on the benefits of nano-scale versions of hydride materials relative to their bulk counterparts, including shorter diffusion distances, new phases with better capacity, reduced heats of adsorption/desorption, faster kinetics, as well as new surface states capable of catalysing hydrogen dissociation.
- A dramatic improvement in hydrogen cycling capacity and the chemical stability of reversible light metal hydrides to multiple charging/discharging cycles.
- Development of cost-effective off-board regeneration processes and systems for non-reversible light metal hydrides. A high thermodynamic and kinetic barrier invariably exists for chemically recalcitrant products (e.g. alkali metal borates).

High Surface Area Materials

Hydrogen storage capacity has been investigated in a range of activated and nanoporous carbons, zeolites, metal organic framework and polymer porous materials. Hydrogen molecules usually form a physi-sorbed monolayer on the surface, which means that materials with very high surface areas are required to achieve an attractive hydrogen storage capacity. A combination of relatively high pressure and low temperature is required for effective hydrogen storage in porous materials. Currently the maximum amount of hydrogen that can be absorbed is around 6-7wt% at 77K and 20 bar on activated carbons and novel metal-organic framework materials with a surface area of up to $3200m^2/g$. These materials are unlikely to meet the requirements for on-vehicle hydrogen storage but may prove suitable for stationary applications. Basic research issues into high surface area materials include:

- An understanding of how hydrogen interacts with the surface of materials and how the nature of hydrogen bonding with the host framework can be tuned to optimise storage properties.
- A systematic investigation of the effect of size and curvature of nanomaterials on the thermodynamics of hydrogen storage.
- A theoretical assessment and experimental research to see whether such materials can be engineered to reversibly store high levels of hydrogen near room temperature.

Hydrogen Storage in Liquids

A range of liquid-phase organic materials with reversible hydrogen storage capacities of >7 wt% at 200˚C have been developed recently. Selective catalysts enable highly reversible catalytic hydrogenation and dehydrogenation with no significant degradation of the molecules. Acceptable cost and low volatility would allow the use of organic liquid-phase hydrogen storage materials in onboard hydrogen storage systems.

Another potential liquid medium for hydrogen storage is ammonia (NH_3) and its various chemical derivatives. NH_3 has a gravimetric hydrogen content of 17.6 wt% and a temperature of liquefaction of 240K, which corresponds to a pressure of around 8 bar at room temperature. Major materials research areas include the development of:

- Organic systems that can be dehydrogenated at low temperatures and produce hydrogen at feasible pressures.
- Selective, highly reversible hydrogenation and dehydrogenation catalysts, enabling multiple cycles of use with no significant degradation of the organic molecule.
- Selective catalysts for low-temperature decomposition of ammonia.
- Novel liquid and solid ammonia-based storage systems
- Confirm the resistance of materials to stress corrosion and corrosion fatigue in the storage media

6.4 Cross-Cutting Materials Research Areas

Several common basic materials research needs are apparent in any discussion of hydrogen production, storage and use. Such “cross-cutting” areas or themes are also a key source of synergy in hydrogen and fuel cell materials research and development. These cross-cutting themes are important since progress in one area will significantly impact on other areas, thereby accelerating progress across a wide spectrum of activities. This also leads to an integrated approach to the many and varied research challenges in Hydrogen Energy. Such cross-cutting areas are briefly discussed below:

Current materials. Much of the infrastructure for hydrogen distribution will employ currently available materials. Data to allow the safe application must be generated and novel means of ensuring integrity cost effectively need to be explored.

New materials. An over-arching theme centred on the ability to design and tailor advanced materials for particular applications. These new materials synthesised through the entire spectrum of modern synthetic methodologies and techniques. New materials or materials combinations for structural applications need to be inspectable.

Catalysis. There is a need in all areas for specifically designed catalysts with higher activity, higher specificity, higher stability and reduced susceptibility to impurities. Similarly, catalysts are required that lessen, or eliminate, the need for noble metals thereby reducing the cost associated with catalysis. These requirements will involve experimental programmes underpinned by fundamental understanding of catalysis site structure and dynamics at the molecular level.

Nanostructured materials
Nanoscience and nanotechnology have the potential to address many materials performance issues by taking advantage of the distinctive chemical and physical properties of nanostructured systems.

Membranes
Fundamental advances could significantly reduce the cost of meeting the hydrogen purity requirements of fuel cells and other applications. The combination of superior permeable catalysts and membranes constructed from nanostructured hybrid organic/inorganic systems are of particularly importance.

Advanced Instrumentation and Characterisation Techniques
Knowledge of chemical and physical material properties at the nanoscale level can have a significant impact across all areas. Development of new analytical tools to provide atomic-level information will support all aspects of materials programmes on hydrogen energy.

Theory, Modelling, and Simulation areas are essential for new developments in all aspects of hydrogen energy materials, from theoretical studies of the interaction of hydrogen with materials, through catalyst design, new materials design, to the hydrogen embrittlement process. Similarly, understanding of electron transfer processes in solids and interfaces is crucial to enhanced photo-catalysts and photo-electrochemical processes in hydrogen production. Such theory and modelling must be coupled in parallel with basic experimental studies.

Safety and Environmental Issues
Hydrogen is characterised by high diffusivity and inflammability. Hydrogen embrittlement in materials and development of sensitive, selective sensor materials for hydrogen are key research areas.

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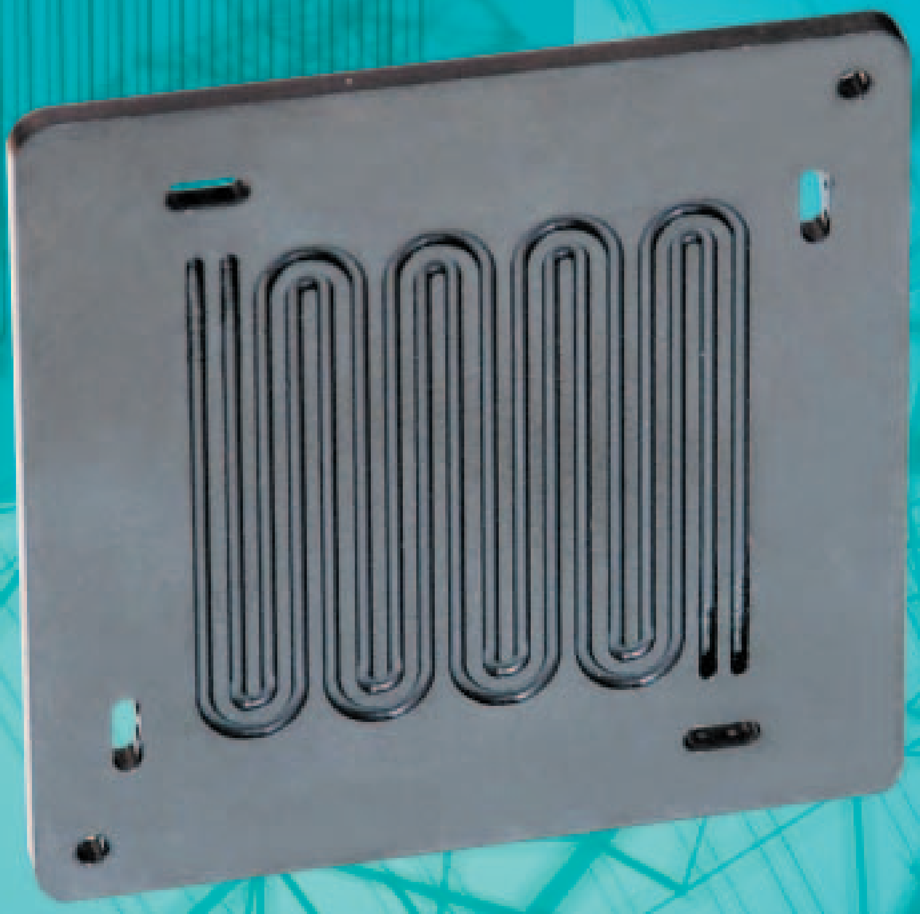


7.0

Fuel Cells

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy.

The basic physical structure of a fuel cell is illustrated in Fig 1. It consists of an electrolyte layer in contact with a porous anode and cathode on either side.

The system is analogous to a battery, though a fuel cell possesses the advantage of being constantly recharged with fresh reactant. Unlike batteries, fuel cell reactants are stored outside the cell and fed to the cell only when power generation is required. Hence, a fuel cell does not consume materials that form an integral part of, or are stored within, its structure.

There are a number of different types of fuel cells using various technologies that are suited to different applications. The best-known fuel cell types are:

- Alkaline Fuel Cells (AFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Direct Methanol Fuel Cells (DMFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Molten Carbonate Fuel Cell (MCFC) and:
- Solid Oxide Fuel Cell (SOFC).

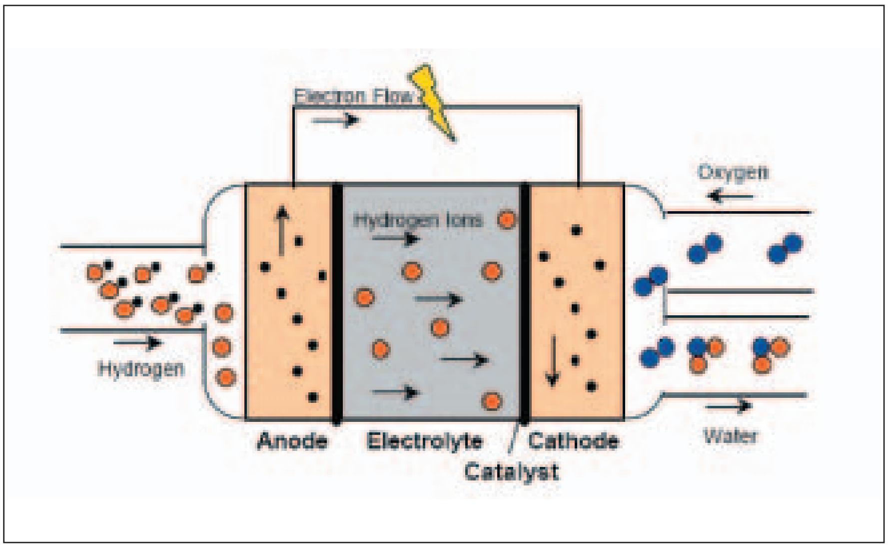
Each device uses a different fuel and applications range in scale from a few mW to MW.

Fuel cells offer a high efficiency route to generating energy that has led to a high degree of global R&D activity. Each fuel cells uses a different range of materials:

Low temperature fuel cell stacks (AFC, PEM & DMFC) operate on a hydrogen or alcohol fuel and rely on metal catalysis, particularly at the cathode, for viable reaction rates. PAFC and high temperature cells use a range of fuels including hydrogen, hydrocarbons and reformates. Table 1 (overleaf) shows the six major fuel cell types. The first four can be classified as low temperature cells, while the final two are high temperature cells. This distinction is becoming less clear as the temperatures of operation converge.

Other fuel cell types such as formic acid fuel cells, boron hydride and direct ethanol fuel cells present further opportunities for new materials. Their power outputs are likely to be exploited in specialist [military] applications in the next 20 years. Each type of cell mentioned above will produce a voltage of typically 1 Volt and a power in the range of a few mW to a Watt. In order to obtain sufficient power for practical applications [excluding small portable power] cells have to be linked together in series or series-parallel to form a stack. Stacked cells also require an interconnect or bipolar plate. The interconnector typically separates one cell from the next and is highly conducting, stable in both oxidising and fuel atmospheres, has a low corrosion rate and a closely matched thermal expansion coefficient to other cell components. All cell and stack components must also offer competitive cost and ease of manufacture.

Fig 1. Schematic of a fuel cell showing the principle of operation.



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7.1 Current status of technology

US and Japan encourage strong academic / industrial interaction and have well funded / coordinated programmes on fuel cell technology. They are well ahead of UK activities. For example, the US SECA (Solid State Energy Conversion Alliance) programme has successfully accelerated development of SOFCs[2]. SECA was established in 1999 to bring together government, industry, and the scientific community to promote development of environmentally friendly SOFC for a variety of energy needs. SECA represents a new model of joint government/private industry technology research and development and effectively channels the use of funding resources.

The SECA programme aims to create fuel cells that will meet Department of Energy (DOE) cost and performance goals. Leading researchers in industry, academia and at national laboratories support industry teams with R&D through a Core Technology Programme. As the teams identify research issues they bring these challenges to the Core Technology Programme for solutions that are shared across all teams. The US government has funded the majority of the technology development stage. As technology is readied for commercialisation and potential profits, industry will increase its funding support of SECA to better reflect this shift in focus. The strength of the SECA programme is that it brings all US SOFC capabilities together to work towards common goals.

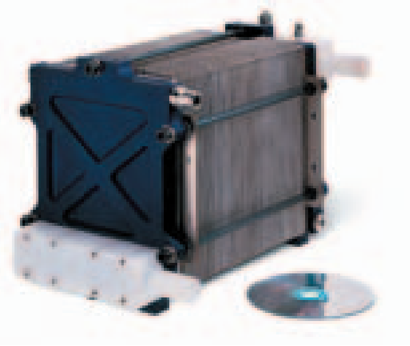

Table 1 The six principal fuel cell types.

Fuel Cell type	Electrolyte	Mobile ion	Operation temp °C	Features	Principal application
Polymer Electrolyte Membrane (PEMFC)	$CF(CF_2)_nOC$ $F_2SO_3^{2-}$	Hydrated H^+	60 - 80	High power density, Pt catalyst, must be kept wet, poisoned by CO	Mobile power
Alkaline (AFC)	KOH	OH^-	50 - 200	High power density, cannot tolerate CO_2	Space flight
Phosphoric Acid (PAFC)	Phosphoric Acid	H^+	~ 220	Medium power density, Pt catalyst sensitive to CO	Stationary power
Direct Methanol (DMFC)	$CF(CF_2)_nOC$ $F_2SO_3^{2-}$ or hydrocarbon membrane	H^+ and OH-(H_2O, CH_3OH)	60 - 120	Medium power density, high Pt content	Electronics Laptops, mobile phones
Molten Carbonate (MCFC)	Alkali metal carbonates	CO_3^{2-}	~ 650	Low power density, Ni Catalyst, needs CO_2 recycle	Stationary power
Solid Oxide (SOFC)	Ceramic YƵG or Doped Ceria	O^{2-}	500 - 1000	Medium power density, accepts CO as a fuel	Stationary power

China and Korea are also investing heavily in academia and industry. Within Europe, German institutes continue to ensure a strong collaboration between universities and business. The EU Framework 7 (FP7) Energy Programme runs from 2007 to 2013. The first call for proposals was issued in December 2006. As part of this scheme a Hydrogen and Fuel Cells Platform (HFP) has been proposed as a public private partnership (PPP), which is to be known as the Joint Technology Initiative (JTI). The JTI is driven by industry with major development activities in fuel cells and hydrogen. Academic institutions and research associations are also represented. Materials are likely to constitute a part of the overall JTI.

There are more than 150 UK companies active in the fuel cell industry, with the vast majority operating at component level. Increasingly, smaller specialist and University 'spin-out' companies are becoming involved. UK knowledge and expertise spans the full supply chain, from materials suppliers to systems integration, and also includes finance and servicing. The UK fuel cell industry has issued a Fuel Cells UK Roadmap[3]. Many UK capabilities have been developed in partnership with companies / organisations from across the world.

The main UK fuel cell strengths at system level include PEMFC, DMFC & SOFC. These activities are the primary focus for industrial investment. Many UK companies have a rich history in fuel cell technology and are among the leading experts in the design of components. The strengths of 'spin-out' companies lie in novel technology and innovative development toward a demonstrator and commercial products.

Market potential for UK companies developing materials and components for fuel cells is global. A comprehensive list of UK companies involved in fuel cells can be found on the Fuel Cells UK website . Materials developers are advised to look toward other resources (e.g. DOE) for global fuel cell developers.

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[1] Fuel Cells UK is the trade association for fuel cells in the UK. http://www.fuelcellsuk.org
[2] http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/
[3] Fuel Cells UK Roadmap: http://www.fuelcellsuk.org/team/Library/Roadmap-Fuel_Cells_UK-final.pdf

[4] Fuel Cells UK Capabilities Guides:
http://www.fuelcellsuk.org/team/Library/CapabilityGuideWithCovers100903.pdf
http://www.fuelcellsuk.org/team/Library/Fuel_Cells_UK_Research_Capability_Guide_2004.pdf

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In order to reach mass markets technologies generally progress through a "hierarchy of needs". Once proof of concept has been established concern shifts sequentially, though with considerable overlap, to matters such as durability, reliability and cost. Lead markets appear when durability and reliability problems have been at least partially resolved. The generic priorities for R&D in both low and high temperature fuel cells can be summarised by following this approach [Figure 2].

UK's industrial strengths are complemented by a world-renowned science and technology base that is continuously delivering innovation into this dynamic industry. Over 35 UK research organisations are highly active in fuel cell and hydrogen research. The Fuel Cells UK Research Capability Guide lists those organisations[4]. The quality of the effort is excellent, with high international standing and good interaction with UK industry. For example, the EPSRC Supergen[5] Fuel Cell Consortium brings together a number of major UK industrial and academic research efforts in PEMFC and SOFC.

One of the main difficulties with driving the development effort is that advances in fuel cell technology needs a multidisciplinary approach. Figure 3 illustrates the foundation of a fuel cell system and illustrates why fuel cells do not sit easily within a single area of expertise.

Sections 3 and 4 below present examples of specific R&D needs for PEMFC membrane electrode assembly (MEA) and SOFC respectively. The generic similarities between different types of fuel cell are summarised in Table 2 at the end of this document. This Table collates the materials-related industrial needs to specific property sets.

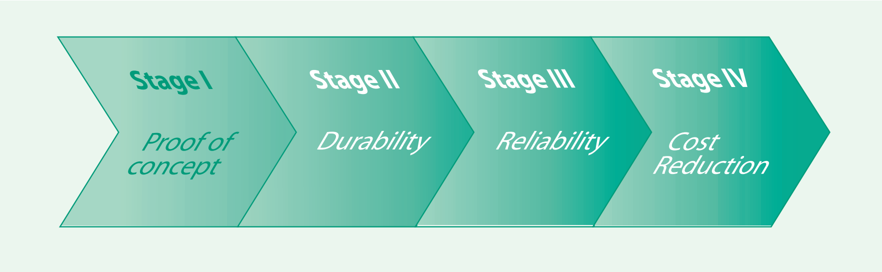


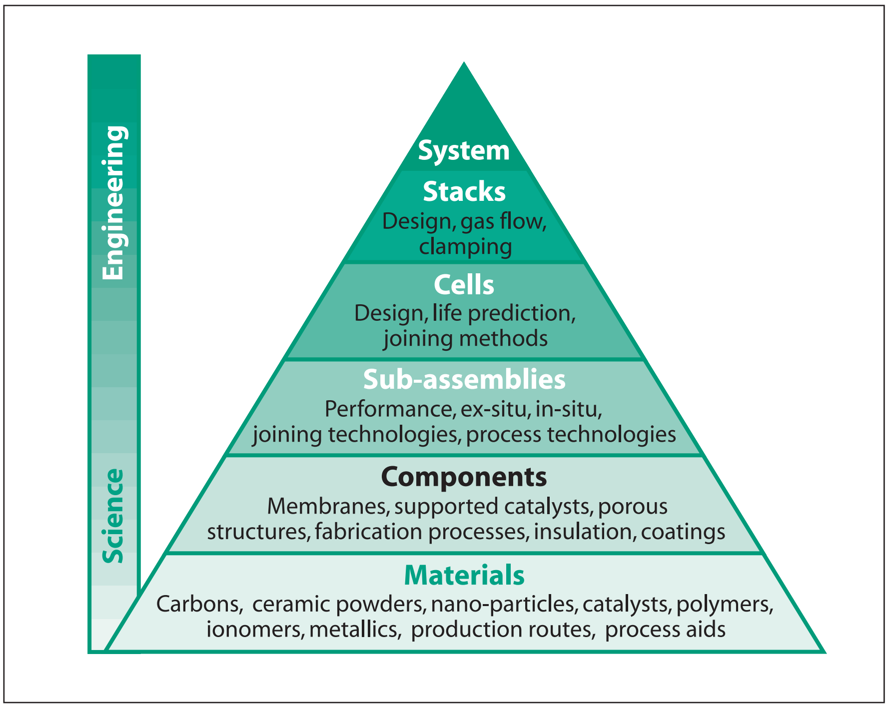
Figure 2. A schematic of the R&D priorities for fuel cell technology

7.2 R&D needs for PEMFCs

For PEMFCs applications, the global supply chain is well populated and will see some consolidation as the industry matures. Some major global manufacturers are UK based, including component suppliers. Industry needs to strengthen links in the supply chain that lead to membrane electrode assembly and encourage innovative activity to produce a suite of new and improved materials and components that feed the developing market. High quality UK research has led to university 'spin-out' companies exploiting innovation in materials and components for low temperature fuel cells. To strengthen this trend, more support from government is needed to initiate/focus R&D efforts in new/improved materials and components. For low temperature fuel cells, effort in materials needs to focus on:

- Membranes
- Catalysts
- Supporting layers
- Bipolar plates
- End plates collectors

Figure 3 Interdisciplinary requirements for fuel cell development.



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[5] http://www.supergenfuelcells.co.uk/

Examples are given below of specific challenges for membrane electrode assembly (MEA):

The challenges for membranes include:

- Identification of rate controlling process in membrane degradation.
- New materials to reduce dependence on water content for proton transport.
- Membranes that maintain conductivity at higher temperatures or dryer conditions.
- Improvement of OH- conducting membranes.
- Membranes with lower gas and MeOH crossover.

The principal challenges for catalysts include:

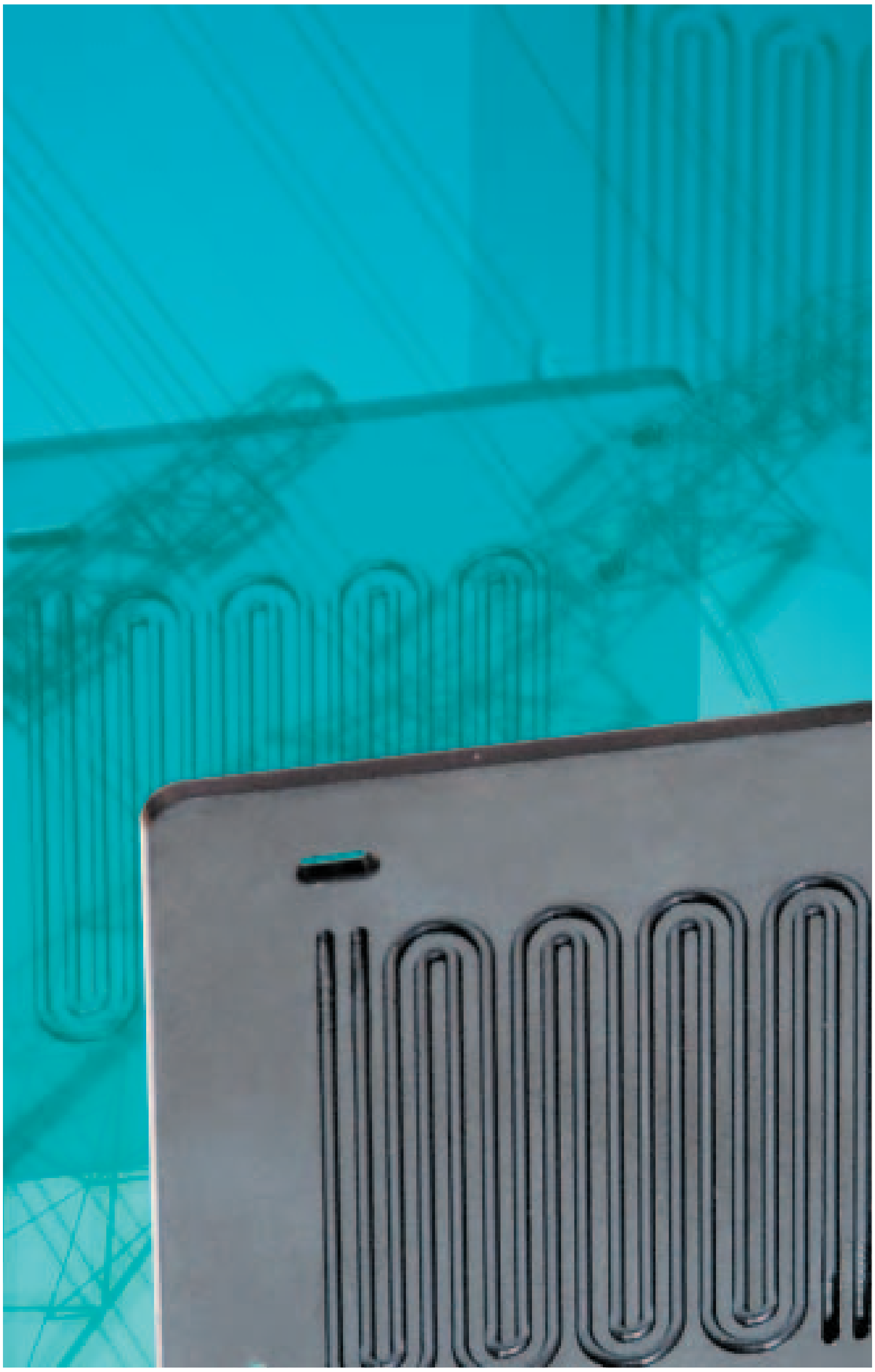
- Mechanisms of O^2 reduction fuel oxidation, poisoning by CO, Pt/Ru effectiveness.
- Better cathode catalysts central to improved performance for automotive applications.
- Catalysts for higher alcohol fuels - more complex molecules.
- More CO tolerant anode catalysts.
- Characterisation of materials e.g. number & type of active sites & their de-activation.
- Simple non-MEA methods of quantifying electro catalyst activity.
- Controlled synthesis methods to produce particular types of active site.
- Availability of lower cost, non PGM catalysts.
- Reduction of catalyst content to bring cost down.

For porous layers, the challenges include:

- Rigorous application of porous electrode theory to the electrochemical reactions.
- Detailed work on understanding existing porosity measurements used in MEAs.

The main challenges for characterisation include:

- Measurement of the location and state of water clusters within porous materials.
- Tools to characterise ionomer properties in the hydrated state.



7.0 Fuel Cells

7.3 Intermediate and High Temperature Fuel Cells

The main focus of activity in high temperature stacks in the UK is on solid oxide fuel cells (SOFCs). These operate from Intermediate Temperatures of around 500°C (IT-SOFC) to High Temperatures up to 1000°C (HT-SOFCs).

They are being developed for auxiliary power units (APUs) and stationary power applications in the kilowatt to Megawatt range. Solid oxide fuel cell development projects exist in Europe, North America, Asia and Australia.

Solid oxide fuel cells and SOFC systems have two different sets of challenges:

- Materials for cell and stack;
- Materials in the components and sub-systems that constitute the balance of plant.

Cell and stack challenges include a wide range of ceramic and metal materials used for anodes, cathodes, electrolytes, inter-connectors etc. New materials with better performance than existing materials are desirable and nano-scale materials may also offer benefits. However all SOFC materials must be produced in greater quantities, with reliable and consistent characteristics and at lower cost.

Material challenges for components and sub-systems are less well recognised. Although not part of the cell and stack, these materials can impact on the operation of cells due to release of material. Thus chromium species released from a variety of stack components will affect the performance of the cell. Alternative alloys and use of protective coatings are key areas for research.

Specific challenges for intermediate and high temperature fuel cells are summarised here:

SOFC materials (electrolyte, anode, cathode and interconnect)

Electrolyte materials: (see powders and processing requirements below)

- Mainly yttria stabilised zirconia (YSZ), and rare earth doped-cerias. Depending on the technology, there will be R&D requirements for thinner, denser and more homogeneous electrolyte microstructures.

Electrode materials:

- The anode (fuel) side of the cell is typically a cermet of commercially available nickel and electrolyte. However the cermet is only available from specialist fuel cell materials suppliers at a high cost.
- Fuel (e.g. sulphur tolerant) anodes required (new materials development).
- Anodes need to be resistant to redox cycles (e.g. fuel cut off) and to temperature cycles (fuel cell being switched on and off).
- The cathode (air) side is a commercially available perovskite ceramic, strontium-doped lanthanum manganite (LSM) or cobalt ferrite (LSCF). The scale-up of material supply is required while maintaining consistency for these materials.
- Cr tolerant cathodes required (new materials development).
- Fabrication and characterisation of controlled electrode microstructures.
- High performance cathodes with improved current collection.

Interconnect materials:

- Metallic materials are used at volume within other technology areas. Commercially available alloys not tailored to SOFC requirements.
- Need for specific alloys with properties for fuel cell environment.
- Lanthanum chromate is a perovskite alternative with similar properties and the same supply chain maturity as LSM.

Powders and processing (electrolyte, anode, cathode and interconnect)

- Consistency of supply requires characterisation of ceramic powders.
  - Controlling powder particle size and stoichiometry.
- Modelling of the sintering process.
- Characterisation of sintered materials.

7.4 Manufacturing and Technology Readiness Levels

Manufacturing Readiness Level (MRL)

The manufacturing readiness level shows how commercialisation of fuel cell technology is being approached by fuel cell developers. The current manufacturing readiness level for intermediate and high temperature fuel cell materials is shown as an example in Figure 4. Supply chain involvement will be critically important in the success of this phase of fuel cell development.

Despite the maturity of some current materials, there is a need to develop and characterise next generation components. Introduction of new materials will potentially reset the MRL status to levels 1-3 (basic principles) as shown in Figure 4.

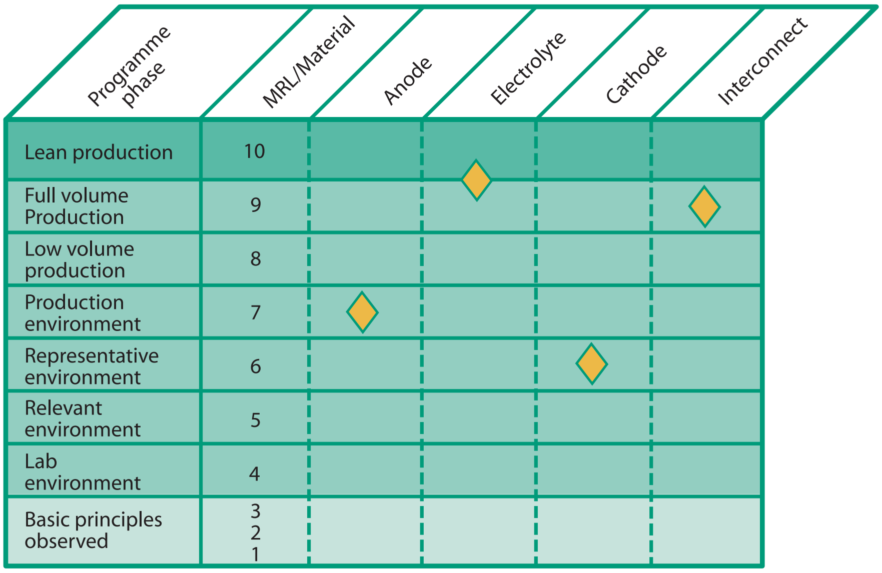


Figure 4 Manufacturing readiness levels for individual SOFC materials.

7.5 Generic Challenges

Fuel cell technology requires the solution of a number of generic challenges for design, fabrication and characterisation. These include:

- Methods to measure and separate ionic and electronic conduction.
- Techniques to create controlled structure layers including pore size distribution, pore alignment, pore connectivity and surface chemistry.
- Control of the 3-phase interface and introduction of nanoscale materials engineering to improve mass transport and catalyst utilisation.
- In-situ techniques for monitoring & assigning causes of performance and durability losses
- Ex-situ measurement of material properties that predict in-cell behaviour.
- Quantitative 3D imaging of nanoscopic structures containing multiphase active components and space (pores).
- Surface science to identify the number and nature of active catalytic sites. This is particularly difficult for real materials.
- High throughput, rapid screening methods for material invention and design.

Practical work on materials development should be supported by efforts to understand theoretical processes by applying modelling techniques in the following applications:

- Understanding of fundamental chemical and physical processes.
- Atomistic modelling of catalytic sites to determine the relative importance of structural and electronic properties.
- Support for experimental work on reaction mechanisms.
- Prediction of better material structures at every length scale.
- Effect of nano-confinement on catalytic activity.
- Effect of solid electrolytes on electron transfer and ion generation processes.
- Construction of multi-scale models of components and cells.
- Prediction of fruitful areas for material discovery.

7.6 Future Opportunities for Low and High Temperature Fuel Cells

Supply Chain

Development of the supply chain for fuel cell commercialisation is vital over the next two decades. Table 2 lists examples of the range of materials needed for development of the fuel cell industry within the UK. Materials processing and characterisation tools also need to be developed to aid consistency of the fuel cell fabrication process.

Cost Targets

Cost is currently a major barrier / opportunity for fuel cell commercialisation. Alternative or improved materials help address this in a variety of ways. For example materials that improve the performance of the cells yield increased power density which in turn reduces costs. A major issue facing fuel cell developers is the stacking of fuel cells. Current stacking methods are too expensive to meet cost-competitive targets. Further material cost and process improvement must be aligned with high performance over the lifetime of the fuel cell system. The overall cost of fuel cells is determined by the whole life cycle costs, from raw material extraction through to final disposal at end of life.

7.7 Next Generation - Materials Development

Alternative materials are needed to take fuel cell technology from niche to mass markets in the energy sector. Developing an understanding of electrode materials through modelling and characterisation will lead to contaminant-tolerant electrodes with improved lifetimes. Development efforts in alloys will focus on lifetime and cost issues across the fuel cell types. New coating technologies will offer important opportunities.

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7.8 Drivers for Fuel Cell Markets

Below are listed some of the main potential applications for certain types of fuel cells:

- Replacement of batteries for portable electronics applications.
- Provide high efficiency distributed power only and power and heat for stationary applications.
- Replace low efficiency central generation.
- Provide secure power supply to critical applications.
- Provide power to remote areas.
- Military use; thermal footprint, portability, etc.
- Fuel flexibility; either directly or via reforming.

In all applications fuel cells will provide low-emission power for urban applications, including low carbon, low noise, low NO_X and SO_X.

7.9 Legislation and Energy Security

Environmental legislation is increasingly concerned with end-of-life management of products. The automotive and electrical/electronics sectors have been set mandatory recovery and recycling targets by recent European legislation. Although no legislation currently applies to end-of-life management of fuel cells, such legislation is likely in future. Since fuel cells are promoted as a "green" source of power generation, it would be socially unacceptable if any aspect of the lifecycle were to present an unreasonable environmental burden.

Energy security is a vital part of the strategy for meeting future power requirements but must be balanced against the need to reduce harmful emissions from power generation systems. Fuel cell systems can operate independently of the national grid and can use a range of fuels that take advantage of emerging social and political trends in power generation.

The main challenges that fuel cells have to overcome to reach full commercialisation within the next decade are durability, reliability, and cost. Further materials improvements, especially in lower component, manufacturing and system costs will aid commercialisation. Fuel cell development will require legislative incentives and further funding initiatives in order to penetrate lead markets. Forward commitment procurement will be critical in accelerating adoption of fuel cell technology.

7.10 Conclusions

Support for fuel cell materials R&D is needed both to support the existing fledgling industry and to develop next generation technologies.

The majority of current applications are at a critical stage in their early commercialisation. The UK is well placed to capitalise on the needs of the industry but needs to increase its manufacturing readiness. Scale-up to demonstrator and production status will involve:

- More efficient processes leading to lower cost products
- New materials
- Understanding failure mechanisms and durability issues
- Increased durability and reliability
- Manufacturing consistency within and between large-scale batch production.
- Fabrication techniques can then be run on a continuous flow basis.
- Inspection techniques to ensure the supply of high quality components supplied is also vital, and these may need development to find the micro- or nano-scale flaws that lead to failure.

Materials R&D is fundamental at all stages in the development process. UK's strength in linking universities and industry must be maintained and grown. Fuel cell challenges of:

- Increased conductivity for cell and stack components
- Environmentally stable thermal and chemical materials

The multi-disciplinary electrochemical nature of fuel cell technology provides the ideal context for future development of materials knowledge and know-how in the UK.

Table 2. Generic commercial fuel cell materials activities in the UK

Generic Heading	Low Temperature (PEM/DMFC)	Intermediate & High Temperature (SOFC)	Property set[6]	Materials involved	UK involvement
Cell Materials	Membranes/Electrolytes	Electrolytes	Density, ion conductivity mechanical, life permeability control electronic insulator Hydrothermal stability	Polymer films Ceramic films	Research Material supply Component production Mass production ready
	Anode	Anode	Catalysis, fluid flow Three phase boundary optimisation Poisoning, water management Hydrothermal stability	Carbon supports Ceramic support Catalysts	Research Materials supply Component production
	Cathode	Cathode	Catalysis, fluid flow Thee-phase boundary optimisation Poisoning, water management	Carbon supports Catalysts	Research Materials supply Component production
	Gas diffusion layer (GDLs)	Anode support Ceramic support[7] Metal support[8]	Porosity control (for muti-phase fluid flow) Mechanical integrity Conformability (thermal, electrical, ionic) Water management (wetability), contact losses	Carbon fibre, polymer coatings, binders, Cermets	Research Materials supply Component prduction
	Catalysts	Catalysts	Activity Stability Poisoning Quantity reduction	Precious metals Nickel oxides Other non-precious metals	Research Materials supply Component production Mass production ready
Stack Materials	Bi-polar plates (BPPs)	Interconnects	Electric conductivity Gas tightness Flow field formation Thermal conductivity CTE match	Carbons Conductive polymer composites Stainless steels	Research Materials supply Component production
	Current take off	Current take off	Electrical conductivity		Research Materials supply Component production
	Metal BPP coatings	Metal interconnect coatings	CTE match Electrical conductivity CTE match Mechanical integrity Chemical inert in use environment		Research Materials supply
	Seals	Seals	Gas permeability Fluid compatibility (corrosion/poisoning) CTE matching Disassembly Creep resistance	Elastomers Polymers Glass ceramics Mineral compacts Welds	Research Materials supply Component production
	Clamping	Clamping	Physical performance Creep resistance	Polymer composites Steels	Research Materials supply Component production
System Materials	–	Thermal insulation	Low thermal conductivity Low volume	Ceramic fibre, foam, hollow spheres, etc	Research Materials supply Component production
	Pump materials	Pump materials	Fluid compatibility (corrosion, poisoning etc)	Polymers, stainless steels, Ceramic linings/coatings	Research Materials supply Component production
	Pipe work	Pipe work	Fluid compatibility (corrosion, poisoning etc) Gas permeability	Polymers Steels Coatings	Research Materials supply Component production
	Thermal management	Thermal management	Fluid compatibility (corrosion, poisoning etc) Conductivity	Steels Coatings	Research Materials supply Component production
Overall			Cost and quantity reduction to drive commersial readiness and volumetric power density	All above	All above

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[6] All property sets should be 'under use environment; i.e. temperature, chemical, physical'
[7] RRFCS spinel tube support
[8] CERES Power porous metal support

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8.2 Barriers to Adoption of PV
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8.0

Solar energy

Capture of solar energy can take one of two forms - either solar thermal or photovoltaic (PV). The former entails solar heating of water, which is passed through a heat exchanger to heat domestic water. In contrast PV systems generate electricity by absorption of solar energy in a charge generating material, such as a semiconductor, light absorbing dye or organic conductor. In the UK both forms of solar energy contribute to micro-generation.

Large, stand-alone PV installations exist in California, Spain, Germany and elsewhere but are unlikely to be considered seriously in the UK. The UK approach is to integrate solar energy generation into buildings and connect the resulting excess power into the distribution network. PV is the only renewable energy that can be used effectively in the urban environment. Around 20% of our electricity needs might be supplied by PV, but at this level of penetration, consideration would need to be given to distribution management issues and energy storage. Solar heating systems have been available for 20 years whereas recent rapid expansion in global PV module production to over 2GW in 2006 has had little impact in the UK market.

There is a ready supply of solar radiation in the UK. The UK annual solar insolation figures are in the range 1000-1300 kWh/m^2. In Spain this rises to 2000 kWh/m^2. Although, more southern climes offer a higher annual insolation rates, the available solar energy in Northern Europe is sufficient to meet a substantial proportion of our energy needs. The challenge is to convert a significant proportion of this into electricity and manage the diurnal and annual variations in electricity production. In the UK we have sufficient unused surfaces on building roofs and façades to generate more solar electricity than we could utilize. Issues associated with implementing this technology mainly involve PV module efficiency and cost. Once installed, PV systems require little maintenance but the capital cost of PV modules and the balance of systems for network connection are significant barriers to wider adoption.

Photovoltaic materials

Photovoltaics includes a range of current technologies:

- Well established crystalline silicon technology
- Numerous types of thin-film technology including:
- amorphous silicon
- compound semiconductors (GaInP/GaAs)
- polycrystalline compound semiconductor (CIGS, CdTe)
- Dye-sensitised (Gratzel) cells
- Newer nanocrystalline and polymer technologies

There is a range of potential solutions to match most requirements including the important issue of reducing the cost [per peak-Watt] of PV-generated power. Cost is dependent upon a number of factors including:

- Conversion efficiency
- Materials costs and yields
- Energy costs and throughput
- Capital costs.

For example, crystalline silicon technology achieves relatively high conversion efficiency in production at around 18% (more than half of the theoretical maximum limit), but material costs are high compared with thin-film technologies. Purified silicon feedstock is currently a limiting factor due to rapid growth in PV technology. Thin-film GaInP/GaAs multi-junction cells have high manufacturing costs but these are offset by higher conversion efficiencies of 35-40%. This technology is finding increased interest for concentrators in terrestrial applications. Polycrystalline thin-film technologies have lower conversion efficiencies (typically around 10%) and potentially lower manufacturing costs. Some newer technologies have conversion efficiencies of only a few percent but are potentially extremely cheap to produce. R&D into PV materials and manufacturing technology is helping the industry to reduce the cost per Watt to competitive levels.

8.0

Solar energy

8.1 The Market for Photovoltaics

Global Context

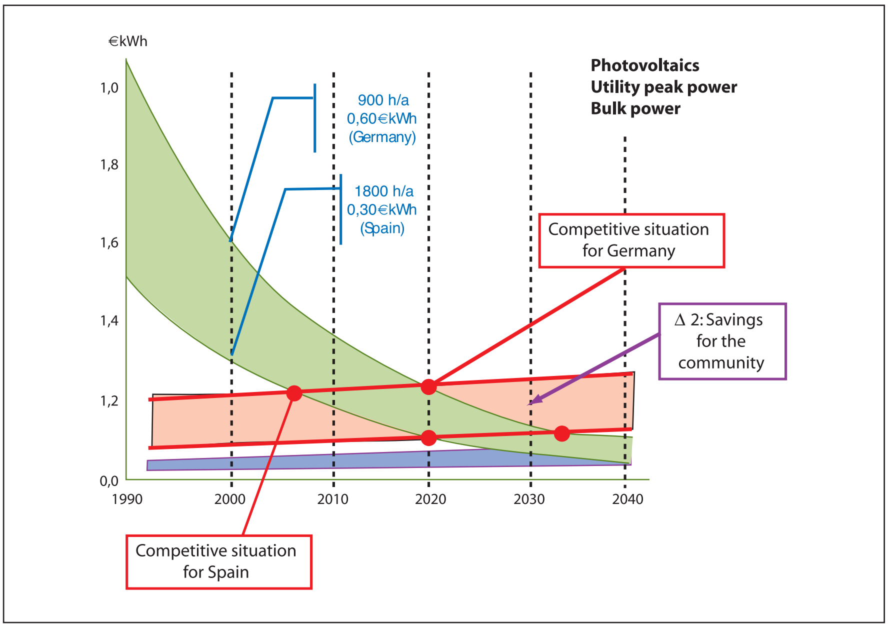
In 2006 manufacturer shipments of PV cells were 1,982MW, a 41% increase over the previous year. Total PV cell production was 2,536MW, indicating increased production capacity to meet demand. In 2000 PV cell production was only at 287MW. Between 2000 & 2006 there was an average growth of 40% p/a.

Over the last 10 years, the proportion of global grid-connected PV has increased from 29% to 78%, largely due to government support projects. This period has seen a dramatic increase in installation of grid connected PV from a mere 34.8 MW in 1995. Japan, Germany and USA accounted for 81% of the new global PV installations in 2006. Not surprisingly it is in these 3 countries where the PV module manufacturing industry is most vigorous.

UK context

The current level of adoption of PV in the UK has been boosted by BERR initiatives such as the BIPV demonstrator programme and PV modules for domestic roofs but the rate of installation is small compared with our major competitors. UK industry does however have the potential to take advantage of a strong PV materials R&D programme. Sharp, the world's largest producer of PV modules has its European production facility in North Wales and UK production is being increased to 220MW per year. In addition UK has a thin film PV manufacture at ICP Solar in Bridgend and a new £60M investment to build a dye sensitised solar cell manufacturing plant in Cardiff. Cardiff is also the headquarters of IQE plc, the world's foremost compound semiconductor epi-wafer manufacturer, who have considerable expertise in materials for use in concentrator PV applications. In the North East, Romag manufacture innovative modules and NaREC have a silicon cell development facility that is capable of small-scale manufacture. PV Crystalox in Oxfordshire is one of the world's major suppliers of multi-crystalline silicon for cell manufacture.

Fig 1: Projected Reduction in PV Energy costs in Europe. Reproduced from the European Photovoltaic Industry Association (EPIA) Roadmap.



8.2 Barriers to Adoption of PV

The cost of buying and installing PV modules is the major barrier to wider adoption of this technology but this is mitigated in adopter countries through strong incentive schemes. To the cost of the module must be added the balance of systems costs that include the mounting structure, cabling, DC-AC inverter and tracker electronics that enable users to connect to the grid and use common AC appliances. The relative cost of the module and the balance of systems depend on the size of installation but as a guide, for domestic installations the module cost is roughly half the total installed cost. Once the system is in place, it is maintenance-free and the fuel is free. However, placing all the costs up-front acts as a significant barrier to installation of PV and makes the cost per energy yield somewhat artificial. Annual energy yields can be calculated with reasonable accuracy but the initial capital cost has to be amortized over many years for economic comparisons against current domestic electricity prices. An alternative perspective is to assume that the module will produce electricity within 20% of its initial rating over 25 years and use this as the basis for calculating the energy price. Figure 1 provides an analysis of PV energy prices compared with domestic electricity prices for different parts of Europe to assess when price parity might occur. With increasing production capacity and improvements in module efficiency there has been a steady decrease in solar PV energy prices from over 1 € /kWh in 1990 to the current position of 0.20-0.44 € /kWh, depending on location. PV solar energy will become competitive in all parts of Europe. Timing will depend on fossil fuel electricity prices and the crossover in PV energy price, beyond which PV actually becomes cheaper. Predictions are that PV energy prices in Spain should be competitive now and in Germany in 2020.

Much of the reduction in cost of PV modules has been due to an increased production capacity. Thin film PV systems should be cheaper than silicon cells because of the less expensive semiconductor material per m^2 of panel and the lower temperature processing costs. However, efficiency of thin film PV modules is well below predicted theoretical values at around 8-10%. This compares with crystalline silicon modules at over 15%. In the case of the most efficient single crystal silicon modules efficiencies of 19.7% are reported [for recently announced Sun Power modules]. Hence thin film PV modules will have to be produced at less than half the system cost of crystalline silicon PV in order to be competitive. The success of silicon PV production has led to supply constraints of silicon feedstock, which is unlikely to cause any long-term impact on prices but in the short term has caused a slight price rise. The cheapest single crystal silicon modules sell for 3.23 € /W whereas the lowest price thin film module is significantly lower at 2.25 € /W. Such price comparisons may stimulate more rapid expansion of thin film PV production.

Cost reduction is not just about production capacity but is fundamentally linked to materials and materials processing. The following factors can be considered in the contribution of materials science to cost reduction:

- Improve efficiency of energy conversion at module level.
- Reduced amount of costly semiconductor materials and efficient materials usage.
- Use of cheaper materials.
- Cheaper and lower energy processing combined with high throughput.
- Improved durability and product life

8.3 Description of Different PV Material Technologies

Crystalline Silicon

Crystalline silicon modules are made from individual cells consisting of either single crystal silicon or multi-crystalline silicon wafers. Current wafer thickness is around 200µm. Silicon single crystal and polycrystalline wafers account for around 90% of the world production of PV modules. The need is to meet global demand, increase materials utilisation and reduce cost. Two approaches are being adopted to silicon cost reduction:

- Reduced silicon consumption per Watt peak (g/Wp) and:
- Reduced silicon cost per kg.

Both approaches could be combined. Additional cost reduction exercises include:

a low-cost solar grade silicon feedstock

b high-quality, low-cost crystallization

c high-yield cutting of very thin wafers

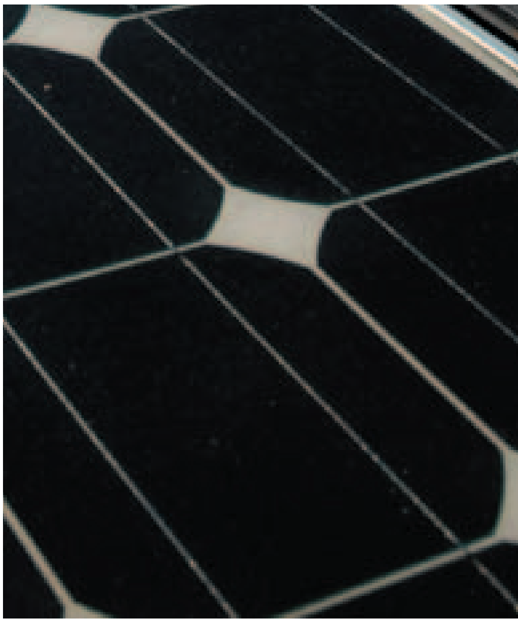
d thin-film wafer equivalents

The above approaches would have the desirable effect of shortening energy payback time for crystalline silicon modules.

Thin film PV

Thin film PV involves deposition of functional layers onto a low cost substrate such as architectural glass. Materials currently used for thin film PV include amorphous and microcrystalline silicon, cadmium telluride and copper gallium indium diselenide. Recent advances in thin film technology and in the use of α-Si have led to α-Si thin film PV modules becoming cost-competitive as part of a wider mix of thin film PV technology.

The common elements to all thin film cells are barrier layers, transparent conducting oxides (TCOs) and back contact layers.



As these are less well developed than crystalline silicon there is the need for production equipment to include in-line diagnostics and enhanced production processes to increase quality and yield. Reproducibility must also be enhanced, together with development of suitable encapsulation processes for both rigid and flexible modules. There is need for more in-depth understanding of the roles of the layers and their properties in the cell operation. The limitations of junctions are also not well understood.

The current drivers for thin film PVs are:

a) Improved efficiency of thin film PV modules.

b) Improved production throughput and yield.

c) Implementation of in situ monitoring and process control

d) Increased production scale.

e) Better understanding of module lifetime issues.

f) Increased materials utilisation.

g) Incorporation of innovative materials.

h) Improved characterisation techniques, in particular for thin film polycrystalline materials.

8.0

Solar energy

Concentrators

Concentrators are an attractive means of using relatively expensive high efficiency (40%) cells such as triple junction GaInP/GaAs/Ge solar cells. By optical concentration of the solar radiation, the area of the cells can be reduced by a factor of 1000 hence reducing material costs. These modules are now seriously being considered for terrestrial applications and have the potential for low cost solar energy conversion. For UK applications the concentrators would have to accommodate a high degree of indirect solar irradiance. The need is to achieve high light concentration without mechanical tracking of the sun. The requirements are:

a) Optical design of lenses from cheap materials such as plastics.

b) Development of efficient photo-luminescent concentrators and light guiding to the PV collectors.

c) Development of improved methods for characterising optical conversion materials for concentrators.

d) Materials integration.

Excitonic cells

Excitonic cells are organic absorber materials although some, such as the dye sensitised (Gratzel cell) are hybrids with porous titania as the electron collector. They are thin film PV cells and can be deposited onto glass, plastic or metal substrates. As with inorganic thin film PV, the TCO is an important part of the cell structure. Current drivers are:

- Understanding the charge conduction (excitonic) conduction mechanisms
- Replacing the liquid redox couple with a suitable polymer and development of new p-type polymers
- Effective utilisation of the solar spectrum
- Development and evaluation of new materials

8.4 PV Materials R&D Challenges

Crystalline silicon

- Low energy conversion of quartz-to-silicon (e.g. electrolysis)
- Advanced crystal growth techniques (e.g. continuous-feed casting or multi-zone refining)
- Silicon ribbon growth
- High efficiency cell structures
- Rear contact cells, enabling low-cost high-volume automated assembly
- Module materials (e.g. polymers) for improved stability and longevity

Thin film PV

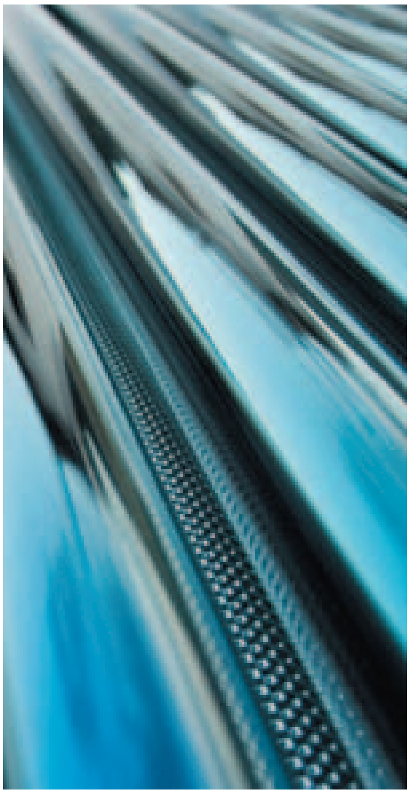
- Alternative TCOs (including p-type materials, higher mobility n-type materials, light trapping)
- Materials and photonic nano-structures for light trapping/harvesting, including optimisation for large areas
- Cell concepts for flexible substrates
- Large area module production equipment, designed for low energy, low materials usage
- Roll to roll processing for flexible substrates
- High throughput testing and quality control for roll to roll and in-line processing
- Research into improved thin film deposition technology such as plasma deposition, MOCVD and electro-deposition
- Sustainable new materials.

Concentrator PV

- Use of low-cost plastic optics for concentrators
- Routes to high volume manufacture of very high efficiency multi-junction cells
- Innovative concentrator designs to capture light over a wide angular range.

Excitonic PV

- Low bandgap semiconducting polymers and sensitiser dyes
- Low cost replacement for ITO as transparent conductor
- Nanostructured organic donor/acceptor heterojunctions
- Low cost environmental encapsulation (oxygen/water barriers on plastic substrates)
- Development of materials manufacturing technology for dye sensitised and polymer solar cells, to include monitoring and in-line materials characterisation



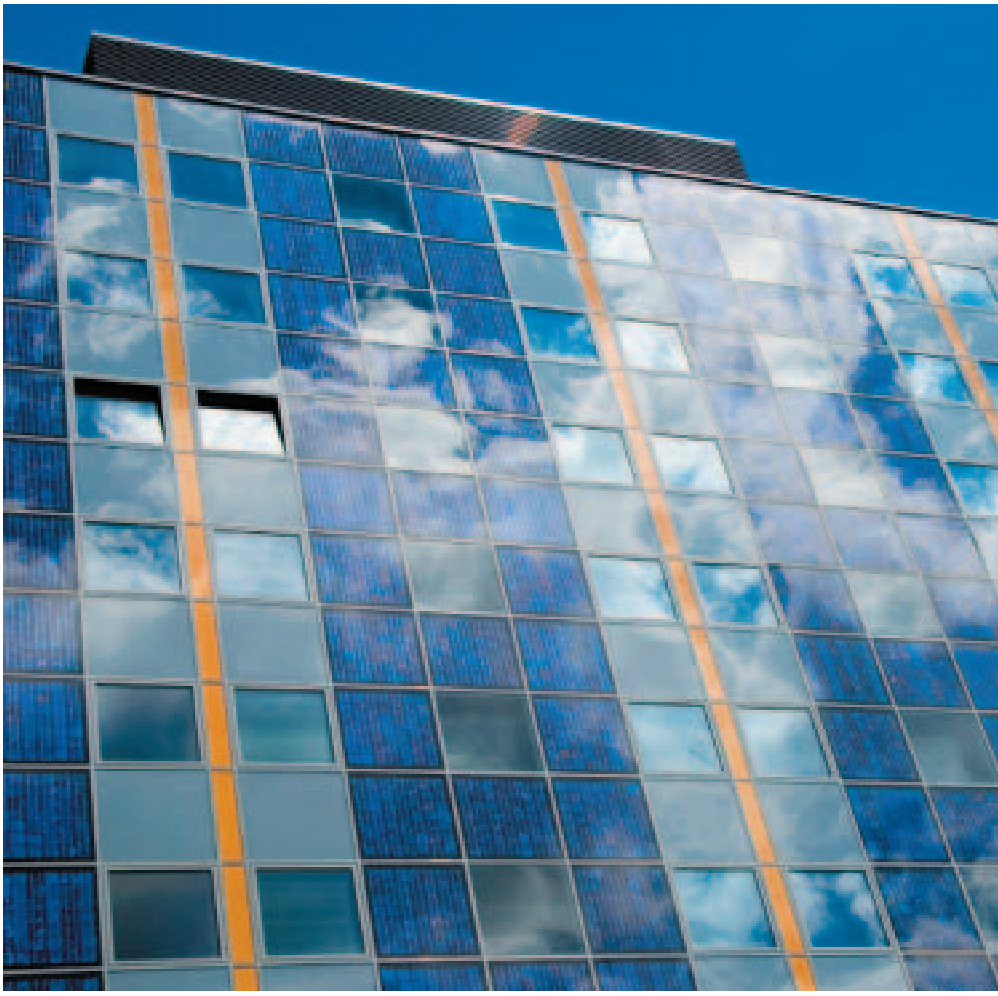
8.5 Solar Heating Materials R&D Challenges

* Antireflective coatings
* Cheap thermal conductors
* Life-time testing of materials

8.6 Eco-friendliness

PV installations can be incorporated into buildings or installed as stand-alone devices. Incorporation into either small domestic or large commercial/public buildings offers minimum impact on the urban environment. PV does not require a fuel supply chain and at point of use there are zero emissions. However, as production capacity increases, more consideration will have to be given to materials processing and the potential for toxic emissions and waste. It will not be sufficient for the finished product to be environmentally safe and chemically inert; consideration will also have to be given to the whole materials supply chain and its impact. The key aspects of the eco-friendliness of PV are as follows:

* Integration into buildings does not require land area dedicated to PV.
* No fuel supply chain
* Potential to be attractively incorporated into the fabric of buildings.
* Consideration needs to be given to materials supply and management of toxic materials in PV cell and module manufacture.



8.7 Recycling and Sustainability

High volume production would reduce availability of materials used in thin film PV production such as indium in some transparent conducting oxides. More abundant, alternative materials need to be sought to ensure materials supply as production volumes increase. Cost effective recovery and recycling of materials will become increasingly important to ensure long-term sustainability. Consideration must also be given to avoiding disposal through landfill. Copper pipes in solar-thermal installations are efficient heat conductors but represent a high materials cost. Similar issues of materials recovery at end of life and sustainability apply to solar-thermal systems.

The lifetime of a PV module depends on the effective lifetime for generating electricity and its effectiveness as a roof or façade panel. The module is normally guaranteed for 25 years whereas its role as a covering has to be effective for at least 60 years to be competitive with existing building materials. These considerations raise the issue of testing and designing longer lifetimes for PV functions to match the design lifetime of the building. The recycle time for the materials would be extended as a natural consequence of greater PV durability. A short- term solution would be to design PV systems that were easily replaced by a more efficient and durable PV product, whilst recycling the older product.

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