Low Carbon and Fuel Cell Technology
Knowledge Transfer Network

Science & Innovation Network

Fuel Cells in India: Opportunities for UK-India Collaboration

Dr. Jonathan Butler, Fuel Cell Today

Dr. David Hart, Imperial College

December 2008

A Report published jointly by the Science and Innovation Network (SIN), British High Commission (BHC), and the UK Low Carbon and Fuel Cell Technology Knowledge Transfer Network (LCFC KTN). This report represents the opinions of the authors alone, and should not be considered to represent the view of any of the organisations above.

Glossary

AFC – Alkaline Fuel Cell.

AIM – Alternative Investment Market (London Stock Exchange).

APU – Auxiliary Power Unit.

ARCI - International Advanced Research Centre for Powder Metallurgy and New Materials.

BHEL – Bharat Heavy Electrical Limited.

CCP – Combined Cooling and Power.

CECRI - Central Electrochemical Research Institute.

CFCT - Centre for Fuel Cell Technology.

CGCRI - Central Glass and Ceramic Research Institute.

(m)CHP – (micro) Combined Heat and Power.

CNG – Compressed Natural Gas.

CSIR - Council for Scientific and Industrial Research.

CWP – Combined Water and Power.

DG – Distributed Generation.

DMFC – Direct Methanol Fuel Cell.

DST – Department of Science and Technology.

GDP – Gross Domestic Product (2004 Purchasing Power Parity).

ICE – Internal Combustion Engine.

IEA – International Energy Agency.

kW – kiloWatt.

LDV – Light Duty Vehicle.

MCFC – Molten Carbonate Fuel Cell.

MNRE – Indian Ministry of New and Renewable Energy.

MW – MegaWatt.

NCCR - National Centre for Catalysis Research.

NCL - National Chemical Laboratory.

NMITLI – New Millennium Indian Technology Leadership Initiative.

NHER – Indian National Hydrogen Energy Roadmap.

PAFC – Phosphoric Acid Fuel Cell.

PE – Private Equity.

PEM – Proton Exchange Membrane (or Polymer Electrolyte Membrane) Fuel Cell.

R&D(&D) – Research and Development (and Demonstration).

SME – Small to Medium Sized Enterprise.

SOFC – Solid Oxide Fuel Cell.

SPIC SF –Southern Petrochemical Industries Corporation Science Foundation.

SUV – Sports Utility Vehicle.

UPS – Uninterruptible Power Supply.

VC – Venture Capital.

Contents

Acknowledgements

The authors wish to thank the Science and Innovation Network and UK Trade and Investment (UKTI) for support and assistance in setting up meetings and with internal travel in India in August 2008, when much of the research for this report was carried out. The authors would also like to thank all companies and organisations who gave up their time to be interviewed during that trip. A syndicated report containing 10-year market forecasts is available from Fuel Cell Today (www.fuelcelltoday.com)

Preface

The pressing need for reliable stationary power for a variety of applications in India, not least for telecoms backup power and uninterruptible power for residential and commercial premises, means that a niche has opened for fuel cell adoption. The imminent commercial take-off of fuel cells for stationary applications in India has implications for unit cost reduction, especially as component manufacturing and system assembly will be done in India, both in the Indian market and in other markets as India begins to manufacture fuel cells for export. The transport sector in India shows promise for buses and 2- and 3-wheeled vehicles, albeit in the longer term, due to the particular sets of operational characteristics required in the Indian market.

The Indian government remains committed to hydrogen and fuel cell technology through its National Hydrogen Energy Roadmap (NHER) and is funding a good deal of research and demonstration though this and other programmes. Various research institutions are carrying out novel and exciting fundamental research on catalysis, membranes and hydrogen storage, much of which is increasingly application-oriented. The industrial sector, particularly some of the larger Indian conglomerates, are becoming interested in buying or licensing the best technology from overseas and adapting it for the Indian market, carrying out their own fundamental research to address issues such as durability and affordability. The latter part of this report gives an overview of UK fuel cell activities with examples of companies, with the final part identifying potential opportunities for UK collaboration with Indian fuel cell organisations from throughout the supply chain, from R&D to end-user. While not wishing to be prescriptive, this part identifies the particular 'fits' and 'gaps' between Indian and UK organisations in the fuel cell sector. The exploration of potential collaborative opportunities is expected to yield a greater degree of engagement and discussion between India and the UK, building on the synergies between the two nations and hopefully leading to mutually beneficial outcomes for the development of the fuel cell sector in both countries. For more information on the fuel cell sector in both India and the UK, and to explore potential collaborative opportunities through the LCFC KTN's project brokering services, please email moderator@fuelcelltoday.com

The Low Carbon and Fuel Cell Technology Knowledge Transfer Network (LCFC KTN) is a business support solution delivered by the UK government through the Technology Strategy Board (TSB). The fuel cell part of the LCFC KTN run by Fuel Cell Today focuses on providing high-quality, information to a range of stakeholders, by providing project brokering support, and assisting in removing barriers to the fuel cell industry, in particular in facilitating international collaboration and the development of supply chains. For more information please see www.lowcarbonfuelcellktn.com

The Science and Innovation Network, British High Commission Science and Innovation Network (SIN) was established by the UK Government in 2000, in response to the growing importance of science, technology and innovation for the country's future.

SIN helps deliver UK success by:

- Facilitating collaboration between UK universities and research laboratories and public and private-sector counterparts abroad; bilateral scientific workshops, conferences and other networking activities.
- Raising awareness of the UK as a global leader in science and innovation; providing expert advice and leadership in support of R&D investment projects; working with UK Trade and Investment to help technology intensive UK based companies; penetrate the supply chains of multi-national enterprises and global markets; providing intelligence to UK innovation networks on overseas science and technology advances.
- Gathering and disseminating best practice in science and innovation policy; developing international frameworks in breakthrough technologies such as stem cell research; promoting UK excellence in science with key international decision-makers.

1. Introduction

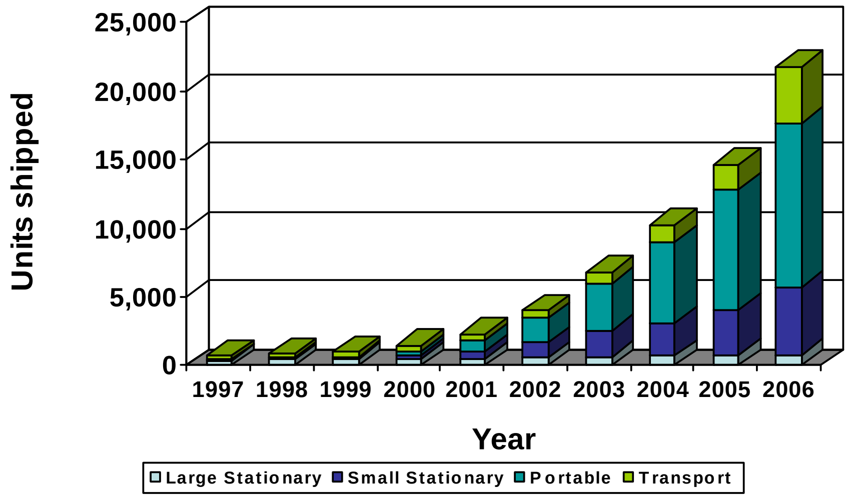
1.1 Background to the report

This report is published by the Science and Innovation Network, British High Commission, and the Low Carbon and Fuel Cell Technology KTN. The information contained in this report is largely based on a number of face-to-face meetings carried out in India in August 2008 between the authors and a range of Indian academic, governmental, and industrial fuel cell specialists as well as a follow-up webinar in November 2008 that brought together representatives from the Indian and UK fuel cell sector to discuss opportunities for UK-India collaboration. The range of organisations met during the trip was aimed at identifying areas of expertise in India and identifying potential complementarities with the UK. The focus of this report is:

- A general overview of the fuel cell and hydrogen markets in India;
- An analysis of the legislative and policy landscape affecting fuel cells;
- A detailed analysis of fuel cell research and development in India;
- A detailed analysis of Indian companies operating in the sector focusing on the key early market area of stationary power and the prospects for fuel cells in transport;
- An analysis of the opportunities for collaborative R&D/commercialisation between UK and Indian organisations.

1.2 Why fuel cells?

A fuel cell is an electrochemical device which converts oxygen and a hydrogen-rich fuel to electricity with heat and water as the principal bi-products. The electricity produced can be used to power any electrical device, ranging from a few Watts to several MegaWatts in output. Fuel cells have the advantages of being highly efficient, low to zero emissions, near-silent, and able to run on a variety of fuel sources (particularly when used in conjunction with a reformer). In addition, fuel cells are reliable and capable of providing uninterruptible power provided they have sufficient fuel. As political attention worldwide focuses on climate change, energy security and air pollution, a significant opportunity exists for fuel cells to replace incumbent technologies in a variety of applications, ranging from stationary, portable and transport power.



Cumulative world fuel cell adoption 1997-2006 broken down by application © Fuel Cell Today

Fuel cells are commercial (i.e. offered for sale, have a written guarantee, and meet the codes and standards of the country in which they are sold) in a variety of applications[1]. These include portable fuel cells in the camping and yachting markets, fuel cell powered toys, niche vehicles such as forklift trucks, and backup and uninterruptible power supplies. The latter application has been boosted by the recent announcement of a large-scale deployment in India, as detailed below.

Several parts of the world have well-established fuel cell industries, such as Japan, North America and parts of Europe. These regions have expertise throughout the fuel cell supply chain, from R&D to component manufacture, systems integration and 'enabling' services such as sales, financing and certification. The UK in particular has a growing supply chain with genuine pockets of industrial and commercial leadership, ranging from world-class fundamental and applied R&D in universities and research establishments, to a range of spin-out and larger corporate players specialising in component manufacture and systems integration. The UK has also been a traditional leader in terms of financing fuel cell start-up companies from the public markets, PE, VC and angel investor funding. The UK government provides broad-based funding for the fuel cell and hydrogen sector, focusing on open innovation and specific challenges to the sector, rather than providing blanket funding for R&D. This has led to a diversity of fuel cell companies who are arguably more

[1] Fuel Cell Today Industry Review 2008 - Fuel Cells: Commercialisation

commercially-orientated than fuel cell companies in countries with a strong reliance on government funding.

Although India's fuel cell industry is less well established, India is an extremely important emerging market, characterised by a need for reliable power for many different applications, an aggressive and forward-looking industrial sector which is increasingly looking overseas to acquire fuel cell technology that will be manufactured in India. India also has a long history of fuel cell R&D coming from its leading universities, as well as a government that is committed to hydrogen and fuel cell technologies as a means to promote economic growth and deliver on energy and environmental policies.

This report will give a background to India's energy landscape, R&D and policy highlights, and an analysis of the market for fuel cells principally in stationary and transport applications. This analysis is aimed at pointing out potential fits and gaps in the Indian fuel cell sector. The final part of the report gives an overview of the fuel cell sector in the UK and leading on from this establishes a number of areas of potential collaboration between the UK and India, highlighting potential opportunities and challenges for the two countries in fuel cells.

1.3 Background to India

India is the world's second most populous country with over a billion inhabitants, and the world's largest democracy by population. It is classed by the World Bank as a low-income country (GDP per capita is US$726), although this classification belies a wide disparity in wealth across Indian society. Around 40% of the population is reported to live on less than $1.25 per day – classed as living in 'extreme poverty'. Around two thirds of Indians live in rural areas, although the agricultural sector is growing at a quarter of the rate of the rest of the economy and there is a good deal of rural to urban migration. The country has had an annual GDP growth rate of around 9% (which came down to 7.6% during the second quarter of 2008 due to the global economic downturn), a rate which is lifting tens of millions of people out of poverty each year and fuelling a consumer boom, particularly in urban areas. At the time of writing, the worsening global economic outlook may have a dramatic effect on India's energy landscape – the fall in oil prices may remove a key driver for alternative technology (i.e. energy security) and perhaps temporarily remove the amount of investment going into fuel cells from governments and companies alike.

Although the agricultural sector continues to be a crucial pillar of the Indian economy, and one that employs a large number of people, industry and the service sector are responsible for employing ever larger numbers of people. The country has a strong manufacturing base, developed mainly during the years of 'import substitution', a policy pursued by successive Indian governments and championed by various high-profile conglomerates such as the Reliance and Tata Groups. This, coupled with the low cost of manufacturing in India makes the country potentially important as a manufacturing base. Small-scale component manufacturing and large-scale vehicle manufacturing (mainly for the domestic and neighbouring south east Asian markets) are two important areas of the Indian industrial sector. India has a well-educated workforce and has seen huge growth in the tertiary service sector in recent years (particularly in IT and telecoms). This has made for a wide disparity in wealth between the growing urban middle class and the rest of the population. Even within the middle class, there is an increasing disparity between salaries of public sector workers and professionals working in industry or services. This is a particular problem for the Indian academic sector. India's research universities (particularly the Indian Institutes of Technology) rank highly worldwide but find it increasingly hard to attract young, high-quality researchers in the face of much higher competing salaries in the industrial and commercial sectors.

2. Macro-scale energy landscape

The Planning Commission's Integrated Energy Policy Report of 2006 (India's first comprehensive energy policy) provides the cornerstone of India's energy policy. Key points relevant to India's energy policy include:

- With over a billion people, India is already the world's **sixth largest energy consumer**, with an annual primary commercial energy consumption of 375.8 million tonnes of oil equivalent.
- India's **fuel mix is heavily dependent on hydrocarbons**. Coal supplies 51% of India's energy needs. Oil and gas are the next largest sources of energy, at 36.4% and 8.8% respectively. Hydro and nuclear lag far behind at 2% and 1.5% respectively.
- **Coal is predicted to continue to deliver over 50% of India's energy needs to 2030** and possibly beyond. Even on the most optimistic scenarios, hydro and nuclear are expected to provide a maximum of around 2% and 4-6% of India's energy requirements in that time scale.

India, like its giant neighbour China, is undergoing unprecedented economic growth at present, with GDP growth rates of 8-9% (higher in some metropolitan areas, with cities such as Delhi and Bangalore having seen 14-15% growth rates over the past few years), millions of people being lifted out of poverty each year, and an ever more resource-hungry and aspirational middle class. India is the world's largest democracy, with a vibrant and intelligent free press, and political leadership at the national scale which is increasingly outward-looking and has sought to dismantle the restrictive licensing and permitting regime that many observers believe stymied economic growth in India up until the early 1990s. With the current financial crisis affecting economies around the world, India appears to have survived relatively unscathed to date, although a worldwide or even regional recession would undoubtedly subdue GDP growth and potentially have significant and long-lasting consequences for India's economy and future development plans.

India's main political challenges at present include maintaining the current rate of GDP growth and ensuring the very poorest section of society benefit from this growth (a third of the world's poorest people live in India according to the UK Department for International Development, DfID). Crucial to maintaining the rate of economic growth of the past few years is building the infrastructure to cope with present demands and support future growth. This means heavy investment in roads, rail, ports, telecoms, and, above all, energy. India's energy landscape is characterised by the country running to stand still - major infrastructural investment is required to even cope with current demands, not taking account of 'new growth' areas such as mobile phones (uptake of mobile phones is occurring at a remarkable rate, as discussed below) and call centres.

The three key challenges in India's overall energy landscape are:

1. Addressing the need for electrical power to maintain economic growth, in the face of a widening disparity between grid supply and demand;
2. Responding to growing concerns over energy security, particularly imported oil;
3. Addressing air pollution in urban areas and wider climate change issues.

These challenges are discussed below in the context of being potential drivers for fuel cell adoption.

2.1 Electrical power for economic growth

There is a good deal of discussion about the gap between electrical power supply and the growing demand from a booming economy. India's coal fired electricity generating capacity is only increasing at around 4,000 MW per annum, compared with the estimated 15,000 MW annual increase required for India to maintain its ambitious rates of economic growth. This energy gap is a key challenge for India's energy sector. The resultant unreliability of grid infrastructure, with typically 5-6 hours a day of power cuts in many cities, is one of the main drivers for the adoption of distributed (or 'captive power') generation whereby entities ranging from individual households to entire industrial sites generate power for their own exclusive consumption. Another is the fact that there are around 55,000 villages which are more than 200 km from the national grid infrastructure. PriceWaterhouseCoopers has estimated that around 20,000 MW is produced by captive generation each year. At present, captive power encompasses diesel gensets, wind and solar generation. Fuel cells also have the imminent potential to fit into a range of captive power niches. The National Electricity Policy envisages that the per capita availability of electricity will be increased to over 1000 units by 2012. The per capita consumption of power in the country in 2005-06 as calculated by the Central Electricity Authority has been about 631 Kilowatt Hours. Based on the information released, even in 2012, per capita availability of power in India would be woefully short of current first world benchmarks. Also current statewise consumption data reveals large disparities between states (see table).

S. NO.	Name of the State /U.T.s	Per Capita Consumption of Electricity (kWh)
1.	Haryana -	1090.39
2.	Himachal Pradesh	765.86
3.	Jammu & Kashmir -	711.01
4.	Punjab -	1436.79
5.	Rajasthan	572.20
6.	Uttar Pradesh	311.82
7.	Uttarakhand	654.84
8.	Chandigarh	1553.96
9.	Delhi	1766.94
	Sub – Total (NR)	**602.56**
1.	Gujarat	1283.77
2.	Madhya Pradesh	580.34
3.	Chhattisgarh	685.81
4.	Maharashtra	934.43
5.	Goa	1970.08
6.	Daman & Diu	8300.12
7.	D. & N Haveli	11567.67
	Sub - Total (WR)	**916.28**
1.	Andhra Pradesh	723.10
2.	Karnataka	720.43
3.	Kerala	424.13
4.	Tamil Nadu	976.81
5.	Lakshadweep	368.29
6.	Pondicherry	2509.25
	Sub – Total (SR)	**757.79**
1.	Bihar	85.86
2.	Jharkhand	548.74
3.	Orissa	633.93
4.	West Bengal	380.61
5.	A.& N. Islands	407.77
6.	Sikkim	429.81
	Sub - Total (ER)	**332.21**
1.	Assam	170.65
2.	Manipur	215.21
3.	Meghalaya	517.54
4.	Nagaland	179.34
5.	Tripura	190.62
6.	Arunachal Pradesh	297.66
7.	Mizoram	250.15
	Sub – Total (NER)	**201.44**
	Total (All India)	**631.41**

Statewise gross annual per capita consumption of electricity during 2005-6 (Utilities and Non-Utilities). (Source: Central Electricity Authority, courtesy of Baiju Nainan, RIL)

2.2 Energy security

Although some of India's energy generation comes from domestic crude oil, around 70% of India's crude oil for transport is currently imported (113 million tonnes of oil equivalent (MtOE) per year are imported compared with 33 Mt produced domestically). This dependence on imported oil is expensive, costing £30 billion ($60 billion), according to the IEA, and adding to India's balance of payments deficit. It also raises concerns about security of supply at a time of high oil prices for a country with historically difficult relations with some of its neighbours. In addition to serving the petrochemical industry, India's domestic and imported crude oil fuels the country's growing vehicle fleet of some 9 million passenger cars (mainly gasoline) and 11 million commercial vehicles (mainly diesel). Diesel and other liquid fuels also play an important role for captive power generation: even some of the poorest households have at least one diesel genset for backup power. Liquid fuels, particularly paraffin, are also used for cooking and lighting in many rural locations. There is a move by the government of India, led by the Ministry of New and Renewable Energy (MNRE) to move the country away from energy supplies based on imported crude oil and towards domestic and renewable energy.

2.3 Pollution

Air pollution is a particular concern in some of India's cities, leading to ill-health, economic losses, and environmental degradation. Such concerns have led certain cities to restrict the use of petrol and diesel vehicles – in cities such as Delhi and Mumbai, local legislation has led to public vehicles, i.e. buses, taxis, and 3-wheeled auto-rickshaws, being converted to run on CNG, with attendant benefits for air quality and, where the CNG is derived from domestic natural gas, energy security. In certain cities, hydrogen is also being blended with CNG as a means to further reduce emissions, improve efficiency and develop a hydrogen infrastructure. At present this hydrogen comes from steam methane reforming although there are plans to develop more sustainable routes to hydrogen production.

Furthermore, around certain historic sites such as the Taj Mahal in Agra, internal combustion engines are banned within a radius of 1 km in order to reduce air pollution. Local restrictions on polluting forms of transport may add up to a significant niche market opportunity for zero emissions fuel cell vehicles. In terms of stationary power, as restrictions tighten on the use of diesel in urban areas, there may be a move towards fuel cell backup and uninterruptible power (UPS) for certain captive power applications.

2.4 Outlook

India's energy landscape may change drastically in the coming years, due to the potential to increase the availability of domestically-produced natural gas and a move away from diesel, and also as an outcome of the recent India-US nuclear deal. The recent discovery of natural gas off the east coast of India is potentially very important in terms of energy security and has led a number of companies competing to become energy service providers to industrial and domestic customers, and also opens up a range of potential energy technologies, from gas to liquids, to fuel cells. Approval has been granted by the 45-nation Nuclear Suppliers Group for a waiver allowing India to trade in nuclear materials and therefore expand its nuclear power industry whilst remaining a non-signatory nation to the Non-Proliferation Treaty. The deal has also been approved by the Bush administration in the US. Now that India is allowed to resume imports of uranium, it will build a new generation of nuclear power stations. This may go some way to meeting India's electrical energy gap, provided the supporting grid infrastructure can also be built. However, the efficiency and cost-effectiveness of pursuing nuclear as opposed to other technologies is uncertain. For new nuclear capacity development, a timescale of 15-20 years is required whereas the opportunity for significant fuel cell adoption may be five years or less depending on the application. Alongside the new nuclear deal, India will continue to develop a diverse energy portfolio, encompassing conventional, renewable as well as novel energy resources.

3. Policy landscape

India's policy as regards fuel cells and hydrogen is driven largely from the Ministry of New and Renewable Energy (MNRE). The remit of the Ministry is obviously considerably greater, including all other renewable energy technologies, but around 30 R&D projects in hydrogen and fuel cells are being supported and it is therefore large in terms of the R&D portfolio. In general terms it ranks well below conventional technologies such as wind and solar.

The Department of Science and Technology (DST) and the Council for Scientific and Industrial Research (CSIR) also undertake and support hydrogen and fuel cell projects, as do both the Department of Atomic Energy and the Department of Space for specific applications, and the Defence Research and Development Organisation.

The main policy objectives for R&D across all sectors are clear: to reduce cost, and improve performance, efficiency, reliability and lifetime of the technologies. Accelerated R&D efforts are underway in solar energy, wind energy, biofuels and hydrogen and fuel cell technologies. It is felt important that both short and long-term goals are worked on, with industry-led R&D to be intensified.

A range of measures has been put into place which have relevance in the wider context, beginning with the 2001 Energy Conservation Act, which set out measures for energy efficiency and conservation. This was followed in 2003 by the Electricity Act, where an overall framework for renewable, including preferential tariffs and quotas, was developed. In 2005 the National Electricity Policy recognised renewable as key options for areas where grid electricity was not feasible or could not be cost-effective, and the 2006 National Tariff Policy stipulated minimum percentages of electricity from renewable sources while taking into account the impact on the retail tariff. Also in 2006, the Rural Electrification Policy considered distributed generation (both renewable and conventional) and work looking at renewable electricity development over the coming 25 years was set out in the Integrated Energy Policy Report.

India is a member of the International Partnership for a Hydrogen Economy (IPHE), an international body with the following stated purpose:

"Serve as a mechanism to organize and implement effective, efficient, and focused international research, development, demonstration and commercial utilization activities that advance the transition to a global hydrogen economy and to provide a forum for advancing policies, and common codes and standards"

Within India, some of this role is adopted under the auspices of the National Hydrogen Energy Board (NHEB), a body set up in 2003 under the chairmanship of Ratan Tata. A National Hydrogen Energy Roadmap (NHER) was produced in 2006 in cooperation between the NHEB and the MNRE, laying out the status of the different hydrogen and fuel cell technologies, identifying key areas for research, development and demonstration, putting them into an Indian context and setting out timelines for addressing them. In addition to RD&D, codes and standards development and co-operation internationally was considered highly important.

The National Hydrogen Energy Roadmap proposed two initiatives:

1. Green Transport (Initiative for Future Transport - GIFT)
    - Developing and demonstrating hydrogen powered IC engine and fuel cell based vehicles ranging from small 2- and 3-wheelers to heavy vehicles through different phases of development.
    - By 2020 about 1 million hydrogen fuelled vehicles, of which:
      75% 2- and 3- wheelers;
      15% cars/taxis;
      10% buses, vans.

2. Green Power Generation (Green Initiative for Power Generation - GIP):
    - Develop and demonstrate hydrogen powered IC engine/turbine and fuel cell based decentralised power generating systems of aggregate capacity of 1000 MW by 2020 of which:
      50 MW capacity small IC engine stand alone generators;
      50 MW capacity stand alone fuel cell power packs;
      900 MW aggregate capacity centralised plants.

    - By 2020, 1000 MW aggregate hydrogen bases power generation capacity to be established.

A focus of this roadmap is capacity building, including the setting up of a National Hydrogen Energy and Fuel Cell Centre.

Dwarka Hydrogen-CNG dispensing station (pictures courtesy of Mr D Chenoy (SIAM)

4. Research Highlights

Indian research in fuel cells follows a pattern similar to that for many other industries, where the vast majority of basic research is done by academic institutions, and applications are developed in industrial organizations. A characteristic of this seems to be that communication between researchers and industry occurs primarily at relatively informal meetings at events and other fora, and that industrial requirements are not necessarily at the forefront when research agendas are being developed. This enables researchers to pursue some of the more fundamental and 'purist' research questions without becoming very applied, which is unlike the situation in the majority of countries in Europe, or in North America.

Historically, Indian companies have primarily been service or product providers and only a limited R&D culture has been developed. Within the pharmaceuticals and semiconductor industries this has changed over recent years, but it is felt by many that the mindset to fully exploit Indian research excellence commercially is lacking. India has some excellent researchers and well-respected organisations in fuel cells and the relevant science and technology. The majority rely heavily on government support, as may be expected for a non-industrially-focused programme. The majority of work is carried out in the Indian Institutes of Technology. In terms of fuel cell work, chemistry and catalysis have a strong role to play and considerable work is being undertaken on lower temperature fuel cell systems such as PEM and DMFC. While others are also under investigation, including SOFC and some aspects of PAFC and MCFC, these appear to have less focus in the near term.

Some relatively fundamental work is being undertaken by industrially-funded researchers, such as those at the Tata Motors Research Centre of the Indian Institute of Science in Bangalore, and work at Reliance Industries on SOFCs. However, the majority of industrial organisations are either performing more applied research, such as integration of fuel cell stacks into systems adapted to local Indian requirements, or looking to invest more in the deployment and operation of systems into specific markets, rather than conducting research at all. However, filing patents in India is a costly and time-consuming process with the result that the majority of academic researchers publish very few patents, though they may make a considerable number of discoveries. Since technology transfer out of academic institutions has not been a focus, with journal publications much more important, this is quite logical. It does mean, however, that potentially valuable basic science may not be exploited to India's benefit.

Judging the absolute number of people involved in fuel cell and hydrogen research in either the UK or India is not easy – the UK pool is spread over both universities and companies, while the Indian pool is more concentrated towards universities and similar research organisations. In addition, the multidisciplinary nature of fuel cells makes the allocation of a researcher – for example on fundamental catalysis – to a particular technology somewhat arbitrary. In very gross terms we got the impression that the numbers of people working on fuel cell-related research in the two countries may be quite similar, though many more are involved in development activities in the UK as a function of the companies that are based there. An indicative estimate would be that several hundred researchers work in different academic institutions in the UK on fuel cell-related issues, supported by both MSc and PhD students. Another two to three hundred people are engaged in industry, not only in research. In Germany, the USA and Japan the figure is considerably greater. We were given the impression that in India perhaps 50 key academics worked in the sector, supported by researchers and students.

The majority of institutions we visited considered that funding for fuel cell research was broadly adequate, but several mentioned problems in attracting good people, given that academic salaries tend to be considerably lower than can be gained in the commercial sector, particularly in view of India's major growth over recent years. A point of interest for us was the fact that while the majority of staff at academic institutions e.g. IITs (Indian Institutes of Technology) and Universities have PhDs, the majority of staff at CSIR labs have BEng or MTech degrees. CSIR has recently announced plans to set up a university, spread across its 38 labs to increase the number of doctoral candidates to boost research output.

Currently, no active network of Indian fuel cell researchers exists, though it was several times identified as being potentially of considerable use. Links within Institutions to different departments performing relevant work are often patchy, as in many other countries. One interesting communication initiative is a weekly telecast outreach exercise that takes place on the internal system linking 45 technical institutions (the majority of which conduct no fuel cell or hydrogen research), and of which IIT Bombay is a part. The system is used for a wide range of purposes, but in this example is used primarily by IIT

Bombay to disseminate knowledge through general and specialist lectures on fuel cells and hydrogen, and not as a network for collaboration.

4.1 Institution visits

We were able to visit a number of institutions in the short period we were in India; these are outlined below. Due to time constraints and availability it was unfortunately not always possible to visit all relevant research groups in a given place, nor to spend as much time with some groups as we would have liked. The notes below therefore inevitably do not do the area of Indian research in fuel cells and hydrogen full justice.

Central Electrochemical Research Institute (CECRI) (Chennai)

CECRI has focused on product development for Indian market based around a wide range of different work on components that has been brought together. The components are typically provided by other organisations such as the National Chemical Laboratory (NCL) in Pune and National Physical Laboratory (NPL) in Delhi. NPL has apparently produced both carbon paper and bipolar plates that perform as well as those commercially available from major market suppliers.

CECRI has developed proprietary knowledge around different PEM-type systems - for hydrogen/air PEM they investigate and develop catalysts, flow-field designs, modified membranes, and also design stacks, including a proprietary 1 kW low humidity ambient stack. Much of the research is focused on the fundamentals, such as increased power density, low humidity operation, reduction of catalyst loading, modified membranes based on nafion, and alternatives to nafion.

They also work on DMFC, particularly on improving the catalyst and reducing methanol crossover across the membrane, and have produced a 50 W 10-cell stack. One more unusual area, brought about by interest from the Indian military, is a direct borohydride fuel cell in which they use hydrogen peroxide as the oxidant. A 5-cell borohydride stack has been developed.

Facilities include a laboratory with several demonstration and test stacks including those above, and electrochemical modelling capability. Some component evaluation for external organisations is also carried out, and CECRI has some strong commercial ties. Their PEM know-how has been transferred to an Indian company called Genex Science and Technology and the two organisations work together to better understand both the science and the market conditions. CECRI looks actively to license its research.

Central Glass and Ceramic Research Institute (CGCRI) (Kolkata)

CGCRI has a strong focus on SOFC product development, with a team of around 25 people. The work has two major phases. The first, till March 2009 is funded by NMITLI and covers research and development from powder to cell components to stacks. Phase 2 of the project must include industrial partners and will focus on the balance of plant and systems. The longer-term goal is to produce a 1-5 kW product for use with biogas, both in villages and/or urban areas.

The SOFC technology is anode--supported thin-film YSZ using a ferritic interconnect and manifold and glass seals, and operating at 750-800°C. Current work is on a 6-cell (10 cm x 10 cm) stack running on hydrogen, though subsequent work will include simulated coal gas and natural gas. Different materials than YSZ are under investigation, as is lower-temperature SOFC.

Centre for Fuel Cell Technology (CFCT) (Chennai). Part of the International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI) (Dept of Sci & Tech)

CFCT is part of ARCI – one of the Department of Science and Technology's autonomous institutions which has a remit to be strongly outward-looking, including collaboration internationally. For example, ARCI has set up two centres in other technology areas in collaboration with Germany, including demonstrations and pilot plants. One is in sol-gel coatings, in partnership with Engineered nanoProducts German AG.

The focus of CFCT is on hydrogen storage, hydrogen generation and fuel cell technology, particularly applications-related. During the period 2004-9 a major project focus has been to develop a 1 kW PEM system for uses such as UPS. The Centre uses commercial membranes but develops catalysts, electrodes, MEAs, stacks, systems etc. They have a hot pressing facility for MEAs, but it takes around 50 minutes and so is rate limiting; they can also screen print electrodes onto any substrate. Advanced characterisation facilities are shared across ARCI, for example the SEM and TEM facilities in Hyderabad. Day-to-day work such as electrochemical testing is done in-house in Chennai. CFCT has undertaken some work on non-noble anode catalysts, and initial tests at 0.6 V of around 100 hrs show no degradation.

CFCT has a number of stacks and systems of different generations on test. One 1 kW stack has demonstrated 1000 hrs of intermittent operation, with 100 hrs continuous, and 3, 5 kW stacks are also running. The stacks are air-cooled with low humidification requirements. A grid-independent 300 W-1 kW CHP system is also being developed. In addition to cell and stack technology CFCT works on other BoP such as inverters, as fluctuating DC levels and simultaneously high AC outputs are not common requirements for conventional inverters. This work is done with industrial partners. An important future project is a fuel cell-powered Indian 2-wheeler where an in-house demonstration will enable issues related to hydrogen storage and other systems aspects to be investigated.

Indian Institute of Technology Bombay (IITB)

IIT Bombay has a long history in energy systems engineering and considerable work in fuel cell-related research across many different departments. The Department of Energy Science and Engineering showcased some of its research for us and described plans to develop a much wider and more focused fuel cell-related research effort within IITB. This is in conjunction with a wider initiative to create new energy research groupings in solar thermal and photovoltaics. Funding comes from MNRE, DST, and CSIR.

The group has members with considerable international experience, including work at and with FZ Jülich in Germany, Rochester Institute of Technology and Los Alamos National Laboratory; and strong links with the American Society of Mechanical Engineers. The group also has active links with KTH in Stockholm. Work within IITB includes development of novel catalysts for PEM and DMFC, using materials such as Ruthenium-Selenium, metal oxides and other non-noble metals, and small-scale fuel cell system development.

Complex hydrides such as boranes and alanates for hydrogen storage are being investigated and tested; and other members of the group have interests in hydrogen production from renewable sources, in fuel cell characterisation, high temperature HT PEM systems and fuel cell flow field optimisation. Work on high temperature PEM is focused on polybenzimidazole (PBI) provided by BASF and the particular research interest is in reducing the temperature of efficient operation from the current 160°C to around 120°C. The aim at IITB is to pull together all the existing fuel cell work around the Institute and continue existing projects but also draw in new ones, and to move from pure research to wider development. The most recent areas of focus are the high temperature PEM mentioned above, and work on intermediate temperature SOFC using micro-tubular cells similar to those originally produced at Keele University, for stacks and systems of 1-2 kWe output.

In addition to the research portfolio, IITB has plans to develop a wide range of teaching including deep specialised courses on fuel cells, reforming etc as minor options, while offering Continuing Eduction/Professional Development courses to professionals. Hopes to instigate a faculty development programme are also high as experienced faculty are lacking in many areas in India. IITB would like to help the development of hydrogen and fuel cell codes and standards in India, the lack of which acts as a barrier to development and uptake of technology. Novel ideas include the possibility of operating a fuel cell shop of some form, to provide educational toys to interest younger students.

Indian Institute of Technology Delhi (IITD)

The Indian Institute of Technology in Delhi is working on a wide range of areas, primarily based around low temperature fuel cells. We visited the Department of Chemical Engineering, one of the main areas for fuel cell research. They have developed a Direct Ethanol Fuel Cell (DEFC) with a performance of 20-30mW/cm^2, using conventional nafion membrane but with a novel bi/tri-metallic catalyst to facilitate breaking of ethanol's carbon-carbon bond to achieve full oxidation. They carry out further work on membranes based on nafion but including doped ceramics and inorganics to enable them to operate at higher temperatures. IITD also has some early development work on direct glucose fuel cells with performance around 20 microW/cm^2, in addition to development of different O_2 reduction and O_2 evolution catalysts. In the past they have also worked on conventional alkaline fuel cells, but now are beginning to concentrate on anion exchange membranes, sometimes known as alkaline PEM. Likewise, work on alkaline electrolysis techniques and catalysts is anticipated to be refocused onto PEM-type electrolysers.

Indian Institute of Science (IISc) Bangalore

The Electrochemistry group in IISc Bangalore has a background in a variety of energy-related fundamental research work, including batteries, conducting polymers, and the fundamentals of fuel cell reactions. They have worked on thin-film micro-batteries and sputtered coatings in addition to lithium-air batteries. One of their current key fuel cell research areas is conducting polymers to replace conventional fuel cell membranes, and in particular the conducting polymer PEDOT. Specific research involves the study of methanol oxidation by PtRu nanoparticles electrochemically deposited onto PEDOT at very low loadings – of the order of 10 micrograms/cm^2 – which nevertheless performs as well as higher loadings of conventional catalyst on conventional membranes. The work is at an early stage but shows interesting results, being stable over a range of methanol concentrations from 0.5-5 Molar for tests of around five hours duration. In the future the test will be designed to fit more closely with potential end-use device requirements, and testing on hydrogen is also envisaged.

National Centre for Catalysis Research (NCCR) (Chennai)

This Centre is comparatively young, having been set up in 2006 with Department of Science & Technology funding. Although already quite active in catalysis research the main priority at this stage is to build and develop resources. The Centre offer a range of specific courses in catalysis, such as a three week intensive course covering all aspects (bio-, photo, electrocatalysis) for research scholars across India.

The Centre has four primary research areas: New Materials; Energy Conversion (both of which have direct relevance to fuel cells); Green Chemistry; and Theoretical and Computational Catalysis. The feeling within the Centre is that DMFC is particularly relevant for India, due to the comparatively simpler fuel distribution infrastructure than hydrogen. However, it was felt that Indian researchers should focus on membrane and electrode research where they have some potential advantage, rather than necessarily looking at all aspects of systems. One idea mentioned was that of reducing crossover through an electrochemistry approach given that MeOH contains oxygen and therefore has polarity. Other practical considerations may influence future direction. For example, Indian industry may be less able at this stage to handle the toxicity and danger inherent in indigenous fluorocarbon manufacture than some overseas organisations, so alternative membrane materials should be a focus. Some materials have been developed that show an order of magnitude better permeability than nafion, though with lower conductivity, but still require further development. NCCR is also looking at new catalyst concepts that are electrochemically similar to platinum, in promoting both oxidation and reduction reactions; and also looking at platinum dispersion to understand if the catalyst support material can be changed from carbon in order to reduce or avoid corrosion. Apparently NCCR has achieved 0.3 mg Pt/cm^2 for a DMFC with acceptable performance which has undergone single cell testing for one year. Further work includes the potential replacement of platinum at the cathode, where work on group 8 metals and some exotic components has apparently led to a material that is as active as platinum.

Tata Motors Research Centre, Indian Institute of Science (Bangalore)

The Tata Research Centre is involved in a number of alternative fuel and vehicle projects but is developing a capability in fuel cells including the use of bought-in stacks (Ballard) with hardware-in-the-loop and Matlab simulation and modelling to assist in the evaluation of the technology and the development of optimised systems. They are currently testing components, and plan to develop a fuel cell/battery hybrid drivetrain for a bus as their first step. While there are currently no plans to develop and build stacks it is important to understand their operating characteristics in order to optimise systems. Additionally, the development of maintenance and support systems in the future will require a sound understanding of stack behaviour.

More generally, the group has interests in bipolar plates, in inverters, in humidification modelling and in compressor/turbine modelling and development. Balance of plant components and systems suited to Indian conditions are an important area for research – Tata believes that the cost of the balance of plant 'could be halved' if it were produced in India rather than overseas. While the primary aim at this stage is buses, smaller vehicles may be developed at a later date. Tata already has strong links to the UK through their European technical centre in Coventry.

The Energy and Resources Institute (TERI) (Delhi)

TERI is a research institution funded from a range of sources including multilateral bodies such as UNEP and the EU, as well as the Indian Government. This means that in some areas it can act independently of particular current funding streams.

TERI has in the past conducted fuel cell research but no longer does so at a fundamental level. Work that was previously done on such things as fuel cell membranes and their manufacturing techniques has been broadened to address pressing problems such as waste water separation and purification. TERI also has expertise in related areas, including hydrogen production from algae and biomass gasification and use of the resulting syngas in energy applications. Apart from the above institutes, the following are also actively working in the area of Fuel cells:

National Chemical Laboratory (Pune)

NCL Pune is the co-ordinating institution for the New Millennium Technology Leadership Initiative (NMITLI). Together with three industrial collaborators, (the R&D unit of Bharat Heavy Electricals Ltd; Sud Chemie India and SPIC Science Foundation), NCL Pune successfully demonstrated a 5 kW hydrogen-based fuel cell, with both stationary and mobile applications before a high-level technical committee of the council for scientific and industrial research (CSIR) in 2004.

Hydrogen Energy Centre, Banaras Hindu University (BHU), Banaras

BHU is working on various aspects of hydrogen technology, including production, storage and applications. BHU is developing solar photoelectrochemical electrolysis of water; hydrogen storage using intermetallic and complex hydride systems, as well as carbon nanofibres. The University's work on applications has mainly focused on hydrogen ICEs for vehicles.

University of Rajasthan, Jaipur

The University of Rajasthan is working on development of polymer membrane gas filters for hydrogen purification.

A number of Indian universities have collaborations with leading centres in the world. These include:

- SRM University (Tamil Nadu) Collaboration with Queen's University, Canada
- Nissan has set up R&D enterprise in Chennai for their global fuel cell efforts, perhaps indicating how they value fuel cell R&D in India for their future growth.

(There are also various private institutions and academic institutions involved in fuel cell research in India, as discussed below.)

5. Market developments - Stationary Power

There is a pressing need for stationary power of all types in India, whether off-grid power for individual telecoms base stations or backup power or baseload for residential, commercial or industrial locations. The following section looks at two application areas:

- Telecoms backup power (<10 kW);
- Residential combined heat and power and combined cooling and power (CHP/CCP) (<10kW);

The first of these is seeing some early market commercialisation at present, while the other (for which fuel cells appear a promising fit) is more long term, with several companies making them the focus of their R&D activities. Small scale (2-3 kW) distributed generation (DG) is very important for India, a country with approximately 55,000 villages over 200 km from the national electricity grid. It has been estimated that developing a electricity or natural gas grid to serve such remote villages will take 20-30 years. A significant opportunity therefore exists for fuel cells to be developed as part of an off-grid solution to power supplies, and one that could involve renewable hydrogen production from solar PV. However, as discussed below, natural gas fuelled units could see greater immediate market traction than hydrogen fuelled units.

5.1 Telecoms backup power

One of the key early markets for stationary fuel cells in India is in the mobile telecoms backup power sector. There are currently around 200,000 mobile telecoms sites in India, most of which require backup power supplies for frequent power outages (on average 4-6 hours per day). India has seen tremendous growth in mobile telecoms over the past few years, with over nine million new mobile phone customers in July 2008, and some of the world's cheapest mobile phone calls (as low as US$ 0.01 per minute). India's mobile phone market is a classic example of technological leapfrogging – whereby a new technology effectively supersedes the 'incumbent' technology before the infrastructure for the incumbent technology has been established - in this case a mobile infrastructure has been developed ahead of a conventional land-line infrastructure outside of the major cities. With mobile phones having only 25% market penetration to date, there is clearly significant potential for further growth. On current growth projections, it is estimated that over 500,000 new telecoms backup sites will be required before 2011, with many of these located in rural areas.

Mobile phone base station

Given the unreliability of the national electricity grid, most telecoms base stations are served by backup diesel generators. Although diesel generators have low up-front costs, the embedded and life cycle costs are high, particularly with the crude oil price having been extremely high in the past year. For instance, grid electricity costs around 0.07p/kWh (INR 5/kWh); whereas electricity from backup diesel generators costs around 0.20p/kWh (INR 15 /kWh). It is the telecoms customers for diesel gensets that are being targeted – not only can fuel cells be cost-competitive alongside diesel gensets in terms of running costs, they also suffer from none of the externalities associated with diesel, such as noise and pollution. In terms of its high price and energy security implications, the displacement of diesel generators remains the number one priority for the telecoms backup power industry, and one that fuel cells are making an increasing contribution towards. Fuel cells offer clean power, high efficiency and are potentially capable of running on a diversity of fuels, although to date most of the telecoms backup deployments have been hydrogen fuelled PEMs. Fuel cells are a particularly good fit for 'mission-critical' backup power, for example in remote, inaccessible regions where infrastructure companies are willing to pay a premium for reliable power.

In the telecoms backup power space, there have been several significant recent commercial developments. In May 2008, Ballard Power Systems signed a supply agreement with Acme Telepower, one of India's biggest providers of telecoms infrastructure (see Case Study), to provide PEM stacks for telecoms backup power. This was followed by the announcement of a high-volume development and supply agreement between Acme, Ballard and IdaTech to supply 5 kW natural gas fuelled PEM units. Under this agreement, up to 30,000 fuel cell systems will be delivered by March 2013. The minimum order under the agreement is for 10,000 units for delivery in 2009 and 2010, with two further potential orders of 10,000 units between 2011 and 2013, subject to design and performance criteria being fulfilled ahead of full deployment in 2010. Ballard will supply the stacks, IdaTech will work on balance of plant and systems integration and Acme will manufacture the units in India as part of a joint venture with IdaTech. Acme is currently working on integrating the PEM stacks into products that will begin trials in early 2009. Ballard, as a major stack supplier, is also said to be in talks with Reliance industries on joint ventures in the stationary power business. In August 2008, Plug Power announced it had successfully demonstrated a PEM telecoms backup unit in a rural location in India together with Indian partners Hindustan Petroleum Corporation and Tata Teleservices. The Plug Power GenSys system ran on reformed LPG and provided primary power for the site's total power load, including the base transceiver equipment, air conditioners, and AC lighting. The integrated reformer eliminates the need for hydrogen, thus allowing the system to run on widely-available and easily transportable LPG.

Case study: Acme Telepower

Acme Telepower is one of India's biggest suppliers of telecoms backup power equipment, supplying over 70,000 telecoms sites in the country. For the past few years, the company has been pursuing a policy of diversifying its energy portfolio away from diesel-based generation and towards a range of alternative energy sources. The company has various solar PV, battery and AFC systems commercially available for primary power where a grid infrastructure is absent or for backup power in grid-unstable locations.

As the mobile phone network expands into rural locations, providing reliable telepower for rural hubs is a growing challenge. This challenge is compounded by the need to provide power cheaply in order to keep costs of calls low. One of Acme's key considerations is fuel supply and the company is understood to be looking at various fuelling options including hydrogen, methanol, biogas, and other widely-available reformate fuels that can be easily transported to remote locations.

Since 2006, the company has been working with Astris Energy on integrating their AFC stacks into its backup power systems and has two AFC units currently under demonstration. Since singing a supply agreement with Ballard Power systems for PEM stacks, the company is focusing on demonstrating hydrogen PEM backup power, with the possibility of using various reformed fuels or electrolysis powered by renewables. Fuel cells have the advantage of being capable of providing power for the duration of frequent power outages (several hours a day) and are capable of running for several days between refuelling. Stack life and fuel availability are thus key considerations.

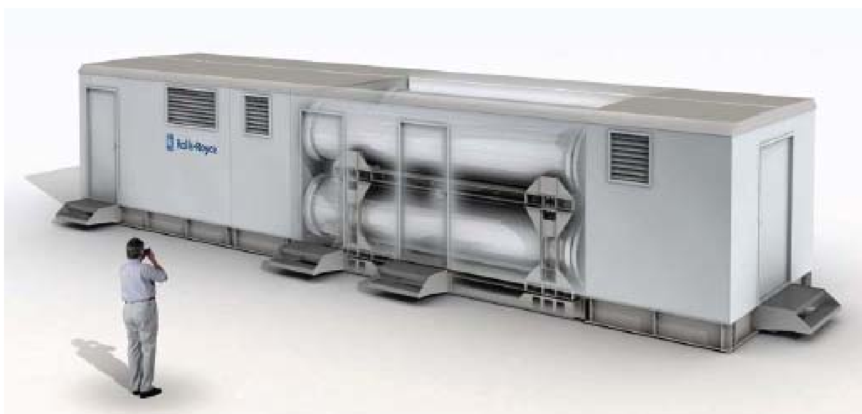
With around 5,000 MW of distributed telecoms power required over the next five years to meet anticipated growth in India (equivalent to tens of thousands of new base station sites), Acme is looking at various options that can compete against diesel gensets. Solar PV is already commercially available, and providing capital cost of fuel cells can be reduced, fuel cells ought to be able to compete. Acme is already active in the emerging telecoms markets of Latin America, the Middle East and southern Africa and is actively looking at expanding its business into other markets. The current business model appears to be to buy or license fuel cell stack technology and to do systems integration and manufacture the systems in India. Acme is a large, potentially acquisitive company that could in future buy a fuel cell company and bring its technology in-house.

The recent agreement with Ballard and IdaTech, which provides a binding commitment to the purchase of 1,000 units in 2009 and 9,000 units in 2010. This agreement also provides Acme exclusive rights for the sale and use of Ballard's fuel cells for stationary power applications in the Indian subcontinent and for telecom backup power applications in the Middle East and Africa (excluding South Africa) through to mid-2011. The agreement provides options for extending these exclusivity provisions into 2011 and 2012, subject to additional binding orders by Acme for at least 10,000 units per year

5.2 Combined Heat and Power and Combined Cooling and Power

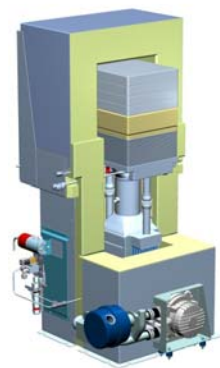
In addition to backup power for discrete power for off-grid locations such as telecoms base stations, there is a pressing need for reliable primary and backup power in the built environment, from individual homes to larger commercial and industrial premises. The principal driver for this is the requirement for reliable, affordable power to fuel continued economic growth. India is in the fortunate position, for all its other energy concerns, of having recently discovered large reserves of offshore natural gas. The government is in the process of issuing licenses for distributing and supplying this gas to customers - how to distribute and use this gas most efficiently and most beneficially is a question that is taxing both government and large corporate players at present. The very real possibility of technology leapfrogging - using fuel cells running on natural gas to generate distributed electrical power as well as heating or cooling for buildings, in a country with little current national gas infrastructure – has now been opened up, and is being pursued aggressively by some of India’s biggest corporate players.

The recent discovery of natural gas in the Krishna Godavari basin, off India’s east coast, has seen several companies vying to develop gas networks for commercial and industrial customers. Large corporates such as Reliance Industries Limited (RIL), who built up a vertically integrated petroleum supply chain from scratch during the 1990s, are looking to develop the downstream part of the business – in particular to develop a self sustaining energy service business in addition to being a distributor. The company has recently established a fuel cell R&D lab to develop natural gas-fuelled SOFCs for stationary captive power applications. The company is looking to develop its own technology in the long term but more immediately is also open to collaborations with other Indian and non-Indian organisations – for example forming links with US-based SOFC developer Bloom Energy**,** General Electric and the Indian power utility National Thermal Power Corporation. RIL has extensive interests in property, particularly hotels and shopping malls, and therefore has ample opportunity to demonstrate its natural gas fuelled SOFC units in residential and commercial settings, providing electrical baseloads and also potentially space heating and cooling. Much of RIL's fuel cell work hinges on gaining regulatory approval to develop a downstream energy business. This is not guaranteed, and there may be other entrants into the market who may also wish to develop fuel cell technology as a means of efficiently generating distributed power from natural gas.



Rolls Royce SOFC power plant. This unit is manufactured by UK based Rolls Royce Fuel Cell Systems

In terms of technology readiness levels, in general low temperature electrolytes are currently more commercially available and, where they are used together with a reformer, can run on a range of fuels. This allows the units to be fuel-flexible, a desirable attribute in places where production and transportation of hydrogen may be difficult. Low temperature fuel cells also offer scalable power for a range of captive power applications. High temperature fuel cells have advantages of offering heating in addition to efficient baseload electricity generation, which can be used both to heat water and, together with adsorption chillers, to provide CCP (since many parts of India do not require CHP). Although CCP may incur an additional capital cost, it may be required for certain critical applications such as cooling as well as power for datacentres and telecoms backup. Certain customers are willing to pay a higher capital cost for the operational advantages that fuel cells bring, not least uninterruptibility of supply, efficiency, noise and air pollution. In some circumstances, fuel cells may also be competitive on a cost basis with gas engines or diesel generators, particularly where a premium is put on certain operational characteristics such as uninterruptibility, for example in a hospital, a datacentre, or a high-end hotel.



SOFC Combined Heat and Power Unit manufactured by UK-based Ceramic Fuel Cells Limited

6. Market developments - Transport and infrastructure

India made 1.5 million vehicles in total in 2005-6 (just over 2% of the world's production of passenger and commercial vehicles). The automotive sector is growing at a rate of 17% per annum, making it one of India's fastest industrial growth sectors. Yet India still only has around 9 million passenger cars, and 11 million commercial vehicles (including buses). Of sales of total passenger vehicles, around 70% are in the 2- and 3-wheeler bracket, with the remainder being more conventional passenger cars. The following section describes the potential for fuel cells in a variety of transport categories: from light and heavy duty vehicles to niche vehicles and infrastructure.

6.1 Light duty vehicles

India's light duty vehicle market is growing at around 17% per year, matching the aspirations of an ever-growing middle class. The country produces around 2% of the world total of light duty vehicles, with these being mainly in the small and sub-compact categories. Of its total vehicle fleet, India has 8 million light duty vehicles and around 11 million heavy duty vehicles. Despite the growing fleet of light duty vehicles (i.e. passenger cars), over 70% of passenger vehicles are two- and three-wheeled vehicles, as discussed below, and the scooter or motorbike remains the main mode of transportation for many Indian families. In a move to develop an affordable car for such families, the Tata group made headlines earlier this year when it unveiled its new 'Nano' model, which will sell at around 1 lakh rupees (£1,400) – a similar price to the motorbikes it seeks to replace. With several automotive OEMs looking to develop their own versions of the '1 lakh car', the stage is increasingly set for considerable growth in the Indian automotive sector, particularly in light duty vehicles.

In terms of manufacturers, the Indian automotive market can be split into three:

- Indian- owned and operated entities such as Tata, Mahindra & Mahindra, and Bajaj, manufacturing in India for the domestic market;
- Joint ventures (JVs) between Indian firms and overseas OEMs such as Maruti Suzuki and Hero Honda (set up in the initial waves of market reforms in the early 1980s), and manufacturing in India for India;

- Foreign owned and operated automotive OEMs who sell their foreign made products in India for a premium (import duties in India for foreign-made cars are currently 104%) and include Mercedes and Toyota.

Manufacturers in all three categories are beginning to look at a range of alternative fuelling options, electric drivetrains, and indeed fuel cells. The rationale for this appears to be continuing concerns over energy security and air pollution as well as (in the case of the first two categories) the need to compete with the best technology from foreign owned OEMs both within the Indian market and in a growing number of export markets.

In the two- and three-wheeler vehicle sector, there is already a move to phase out conventional fuels in favour of less polluting fuels. This has been largely driven by legislation which has called for the use of CNG in public vehicles (buses, taxis and autorickshaws) in order to reduce urban air pollution in certain cities and regions. In certain cities, including Delhi, hydrogen is also being blended with CNG as a means to further reduce emissions, improve efficiency and develop a hydrogen infrastructure. At present this hydrogen comes from steam methane reforming although there are plans to develop more sustainable routes to hydrogen production. At present, the aim is to have hydrogen two-and three-wheelers powered by hydrogen ICEs, rather than fuel cells. Mahindra & Mahindra, one of India's largest three-wheeled vehicle manufacturers has developed a hydrogen ICE 'HyAlfa' three wheeled delivery vehicle, and Bajaj auto has developed a hydrogen ICE three-wheeler. Both companies intend to market these vehicles in cities that are developing a hydrogen/CNG infrastructure. A range of other manufacturers are also developing biofuel and hybrid versions of their two- and three-wheeled vehicles. Although fuel cells may be a good fit for certain two and three-wheeled vehicles (such as postal delivery bikes in Europe), in India the 'fit' is less apparent. Aside from the issue of infrastructure (see below), fuel cells still have high capital costs, which to the operator of an autorickshaw, may be prohibitively high. There is also the issue of durability - fuel cell powered autorickshaws would have to cope with the rigours of often potholed city roads as well as near-continuous operation (most autorickshaws are owned by syndicates who work in shifts). Lastly, two- and three-wheeled vehicles need to be simple to maintain and repair by non-experts. Fuel cells' acceptability for two-and three-wheeled vehicles may therefore be limited, at least in the immediate term.

Fuel cell powered Reva electric car

In the passenger car market, production facilities are currently being expanded across India and a number of manufacturers are looking to develop alternative-fuelled versions of their vehicles. In addition to the investment by Tata in manufacturing the Nano (which, for reasons of political unrest was recently switched from the state of West Bengal to Gujarat) Maruti Suzuki, with 50% of India's passenger car market, is investing over £2 billion ($4 billion) in speeding up business expansion in India through the development of new plant and models. Indian manufacturers and JVs are turning their attention to developing more efficient and less polluting drivetrains, both to improve affordability and also reduce pollution and resource consumption. In terms of activity on fuel cell powered drivetrains, two companies stand out for their commitment to hydrogen and fuel cell technology; Mahindra & Mahindra) and the Reva Electric Car Company (dealt with in the case study below). Mahindra is India's largest tractor, SUV and utility vehicle manufacturer in India, producing 240,000 vehicles per year for India and for export markets. Mahindra's unique selling point is its low cost manufacturing, making its products affordable to a range of customers in and outside of India. The company has been working on advanced technology for several years, and last year unveiled its hydrogen ICE three-wheeler and also has launched a battery-electric hybrid SUV. The company's main focus appears to be on letting the world's big three automotive manufacturers develop the fuel cell technology and then for Mahindra to buy and engineer the drivetrain rather than carry out its own fundamental research. Mahindra seems keen on buying 'black box' fuel cell technology for integration into their vehicles and is actively seeking infrastructure and fuel cell OEM partners with whom to develop future fuel cell vehicles. Mahindra also has interests in areas where fuel cells would be a good potential fit, such as materials handling and household backup power and, as such, may in future seek to carry out demonstration and proof of concept activities with certain partners.

Case study: fuel cells for light duty vehicles – the Reva Electric Car Company

The Reva Electric Car Company is part of the Maini Group, who since 1994 have been manufacturing lead-acid battery-electric plug-in vehicles. To date, Reva has produced around 2,600 vehicles which are mainly sold in two key markets: London, UK (1,000 vehicles sold to date as the G-Wiz); Bangalore, India (800 sold to date) and smaller numbers in other cities in India as well as 11 other countries. Reva's small, plastic-bodied vehicles are designed for city use, where their limited range and generally low speeds makes them ideal as a city commuter vehicle. Aided by the provision of a recharging infrastructure and various government incentives in cities such as London, Reva's electric vehicles have seen considerable uptake and are likely to see further adoption as lighter, extended range lithium ion batteries are adopted in the new 2009 model.

Since 2004, Reva has been working on demonstration fuel cell versions of its electric vehicle and there are now a handful of these operational around the world. These fuel cell vehicles offer the substantial advantage of extended range, quicker refuelling and greater efficiency than their battery counterparts. The vehicles use 1.2 kW Ballard PEM stacks running on compressed hydrogen, with the system hybridised with Reva's battery and regenerative braking system. The company is now looking to develop a second-generation fuel cell electric vehicle based on a pickup platform and using 4-5 kW air cooled systems. Reva is currently in discussion with a number of UK-based organisations including stack suppliers and systems integrators as well as Indian organisation such as CECRI, IISc, IIT-K, and Tata Motors. Reva is looking to roll-out a small demonstration fleet of 25-50 vehicles with on-board real-time diagnostic and data acquisition systems to monitor stack operation, electronic systems and evaluate performance. This test would ideally be done in a city with around 5 hydrogen stations (to act as infrastructure nodes, as the current plug-in infrastructure does). The end of this two-year evaluation period would be the lead-in to commercialisation.

Reva is in the enviable position that its parent organisation, the Maini group, has interests in a broad range of related technologies, such as batteries and polymers, making for potential synergies with the fuel cell/electric car business. With Reva's history of building up a niche market for city electric cars, and expertise in electric drivetrains, the company could be set to make inroads into the market for zero emissions city vehicles that require increased range and shorter refuelling time than purely battery vehicles.

In the Indian context, as in other countries, fuel cell light duty vehicles remain a longer-term technology option, subject to the usual caveats of a viable hydrogen infrastructure, technology readiness and affordable capital cost. However in certain niches, such as zero-emissions city cars, fuel cells may play a role in offering extended range, quicker refuelling and better efficiency than battery models. These could see modest uptake if local regulations mandate zero emissions vehicles.

Mahindra's Hy-Alfa hydrogen ICE 3-wheeled vehicle

6.2 Buses and heavy duty vehicles

Buses are one of the principal forms of public transport in India and, together with heavy duty vehicles (such as freight trucks), they make up the biggest share of vehicle types in India (around 11 million). Buses and trucks alike in the country have to cope with the rigours of often potholed and unmade roads, have to run over long distances for long durations, and also be simple to operate and maintain. Given these constraints, the bus sector in India shows promise as a future potential market for fuel cells and a number of Indian organisations are actively looking to develop demonstration units for this sector. Fuel cells for heavy duty vehicles, on the other hand, show less promise as an immediate-term application, although may have certain near-term niche applications, such as in refrigerated truck trailers.

In terms of buses, Tata is working on developing a fuel cell bus for the 2010 Commonwealth Games in New Delhi. The Games will be a showcase opportunity for the zero-emissions bus, which is to be launched alongside a number of other public transportation projects in the city, including an underground system and a fleet of new, low floored, air-conditioned buses, which are already underway. As with fuel cell bus fleets around the world, the fuel cell buses in Delhi would be a demonstration fleet and not truly commercial deployments (i.e. sold with the intention of generating revenue for their owners). A key challenge for public transportation in India is that the vehicles must be affordable for the operator, which is not the case with the currently high capital costs of fuel cell buses. Another is that buses must be robust enough to deal with the rigours of often-potholed Indian roads, and they must be able to cope with heavy stop-start traffic over hundreds of kilometres each day. In terms of both affordability and technology readiness, fuel cells are unlikely to see large scale deployments over the next few years, although there is ample scope for fuel cell bus demonstrations, particularly in cities which have adopted clean air legislation.

In terms of other heavy duty vehicles such as trucks, which in some parts of the world are seen as ideal candidates for fuel cell APU adoption, there is relatively little scope for fuel cell uptake in the immediate term. Trucks need to be affordable and have low capital costs so that their owner-operators can quickly see returns on their investment. Most trucks, such as those made by Ashok Leyland and Tata, are not endowed with luxuries such as air conditioning and sleeper cabs, and need only to be hardy enough to cope with being driven on rough roads over long distances. However, there may be some exceptions to this, particularly trucks which require APUs for powering on-board chiller equipment. In high-margin markets such as fresh food freight and medical logistics, there is a need for efficient, uninterruptible supplies of power to truck trailers. Where the price point is right, such as delivering fresh food to high-end hotels and restaurants, or for transporting medical equipment, there may be a niche for fuel cell powered truck trailers. Although the potential is there, most truck manufacturers are concentrating on affordable, rugged vehicles with basic specifications.

Two of India's biggest truck and bus manufacturers stand out for their work on hydrogen and to a lesser extent fuel cells: Tata and Ashok Leyland. Tata Motors is working on a range of alternative fuelling options, including 'clean' gasoline and diesel, CNG/LNG and biofuels. The company has been working on hythane powered vehicles since 2006, is now developing pure hydrogen fuelled vehicles and is aiming to develop fuel cell-electric hybrids for commercial markets by 2015. As an interim step, the company is developing the fuel cell bus for the Commonwealth Games. Tata's approach to the bus project is characteristic of an Indian company's approach to fuel cell work: it is importing the PEM stack from Ballard, the electric motor from Siemens and then doing the system integration and developing the balance of plant indigenously. Longer term, the company's aim is to build an Indian manufacturing base with local vendors of balance of plant and electric drivetrains. Tata has strong links with the UK – owning as it does several manufacturing plants based in Britain (through its Jaguar-Land Rover division) as well as a technology centre based in Coventry. The company is actively looking to develop further links on key application areas such as hydrogen storage.

Ashok Leyland is another company which characterises the industry-led development of hydrogen technologies in India. The company, part of the Hinduja Group, is working together with the Society of Indian Automobile Manufacturers (SIAM) on developing hydrogen fuelled vehicles and is following the roadmap outlined in the NHER: i.e. hythane, hydrogen and eventually fuel cell electric motors. Ashok's focus is on delivering low-cost technology where fuel efficiency is key and their vehicles can start earning revenue for their owners as soon as possible. The company has ambitious plans for the expansion of its bus and truck business, which made just over 80,000 vehicles in 2007. Most of its vehicles are currently diesel, with a small number of CNG-fuelled vehicles. It may be anticipated that as hydrogen-CNG mixes become more prevalent in certain cities, Ashok Leyland may produce ever larger numbers of hydrogen ICEs, although it has no current plans to manufacture fuel cells. One market where Ashok may develop hydrogen fuelled vehicles is for the Indian army, one of its largest customers, and one for whom energy security is a crucial issue.

6.3 Niche vehicles

Niche vehicles such as fuel cell forklift trucks are seeing increased market traction in a variety of markets where they represent a real value proposition over incumbent technologies. In certain warehouse environments, such as in food processing and microelectronics manufacturing, fuel cells offer zero emissions, higher operational efficiency and improved refuelling efficiency when compared with incumbent technology such as battery electric forklifts. They also negate the recharging infrastructure and plant required by battery forklifts, although against this a hydrogen or methanol refuelling infrastructure would still be required. India may see some small-scale deployments of niche vehicles such as forklifts, but these are likely to be limited in scale due to affordability issues. There is the possibility that a major airport may choose to move away from ICE ground vehicles for reason of pollution and noise, and towards an all-electric fleet to which fuel cell vehicles would make an important efficiency contribution. As environmental concerns grow, legislated niche markets might also be created for environments such as lakes and inland waterways – providing a boost for fuel cell powered craft, as is happening in certain parts of China.

6.4 Infrastructure

As in many parts of the world, the critical issue for the adoption of fuel cell vehicles is the provision of a hydrogen infrastructure. India is making moves to develop a hydrogen infrastructure in parallel with a fleet of demonstration vehicles, in collaboration with industry, automotive OEMs, international partners, academic institutions, and government support. The NHER provides a framework for doing this, and SIAM, including automotive OEMs and the Indian Oil Corporation are taking a lead on implementing it. The outcomes so far include a hydrogen-CNG ('hythane') refuelling station in Delhi, and a pure hydrogen refuelling station. Both of these use surplus hydrogen from the chlor-alkali industry although there are plans to develop an electrolysis-based hydrogen refueller in Delhi. An Australian company, Eden Energy made headlines in 2008 when it opened the first of the hydrogen-CNG refuelling stations in Delhi. Eden is also working on developing hydrogen – CNG ICE buses in Gujarat and Mumbai. These deployments fit with the path identified in the NHER – i.e. hydrogen-CNG blends, followed by pure hydrogen, then fuel cells. This path also allows incremental improvements on NOx emissions (with hydrogen-CNG blends) and should eventually favour fuel cells once issues of hydrogen storage and infrastructure have been addressed.

CNG powered autorickshaw in Delhi

Public transport, particularly buses, is the most likely fuel cell transport early market in India. As described above, public transport in India is very price-sensitive. As such, hydrogen fuel must cost no more than other incumbent fuel technologies. In the absence of volume hydrogen production, this is perhaps not possible at present without heavy government subsidies. However, hydrogen would not be unique in being subsidised as petrol, diesel and kerosene in India are currently subsidised. Despite the limitations of affordability, current technology readiness and user acceptance, the advent of a hydrogen infrastructure in Delhi and possibly some other cities, economies of scale may be achieved and fleets in the hundreds or even thousands may be envisaged in future. Whether entire city fleets of public transport will move to hydrogen is an interesting question – there is certainly a precedent for the government mandating technology shifts – as seen in various cities' move to CNG over the last decade. In India, by 2004 (6 years after the first rulings that mandated CNG in public vehicles) there were 204,000 CNG vehicles and 198 refuelling stations. The crucial difference with hydrogen is, of course, that hydrogen and fuel cell technologies generally have a higher capital cost than those technologies which they seek to replace, they require a new infrastructure, and they require consumer acceptance and skills training for use in a way that was never required for CNG. Finally, India remains a democracy, and despite the sometimes restrictive practices of various branches of government, is not subject to the kind of top-down control that makes it possible for China, for example, to impose technology choices in certain areas.

Overall, in the transport sector, some OEMs are beginning to procure stacks and develop balance of plant with the longer-term goal of building and indigenous manufacturing base (as is also seen in the stationary sector). As emissions control standards tighten across India - Bharat 4, effectively Euro 4, is being introduced in 11 cities from April 2010, with Bharat 3 (Euro 3) being introduced for the rest of the country in April 2010. This is driving lower emissions vehicle adoption, and even more stringent regulations (such as CNG mandates) are in force in certain cities. The Indian automotive market is an interesting one, where price points are the key decider. As such, fuel cells are unlikely to be adopted widespread in 2- and 3-wheelers, and fuel cell LDVs are likely to be restricted to the high end of the luxury market, although their adoption may depend on the lifting of restrictive import duties. It is likely that there will be some limited deployments of fuel cell buses, heavy duty vehicles and niche transport vehicles.

7. Other market developments

Despite the country's growing middle class, India is not a place well-known for its consumer electronics industry, either as a major manufacturer or consumer and hence fuel cells are not obviously going to play a role here. Although it seems likely that the military may play a role in stimulating the domestic fuel cell industry (for instance through its need for portable power in remote, unforgiving locations), at present the military's priorities in this area are a closely guarded national secret (this also applies to stationary and portable military fuel cell units). Nonetheless, some Indian research institutes' priorities appear to be oriented towards developing improved membrane durability and power density for DMFCs and DBFCs which have imminent portable and consumer electronics applications. India is likely to follow, rather than lead, developments of portable consumer electronics applications. At present, aside from a small proportion of very wealthy consumers, most mobile phone users require only basic functions such as calling and texting and do not require the power hungry functions such as GPS, music and video streaming.

In terms of how R&D might translate into commercial products or outcomes, research expertise in India tends to be on the fundamentals of fuel cell technology, with particular leadership shown by some of the IITs in catalyst development and membrane technology for PEM and DMFC, and ceramic electrolytes and power management for SOFC[2]. Some of these institutions are arguably less commercially focused than their European or North American counterparts, with fewer links with industry and less focus on applications for fuel cells. Nonetheless, their research is no weaker for that, and there are several world authorities on fuel cells, with numerous well-cited peer-reviewed academic journal articles[3] based at the IITs.

[2] E.g. novel membranes (Sahu *et al.*, 2007), Improving Pt utilisation in catalyst layers (Selvarani *et al.*, 2007); reducing methanol crossover in DMFC membranes (Sahu *et al.*, 2008a).
[3] Shukla was recently revealed as the most prolific Indian author of fuel cell papers (1171 total citations) with Santhanam *et al*. (1999) the most cited paper (cited 169 times) (Sahu *et al.*, 2008b)

8. Potential UK collaborators

The UK's energy landscape is markedly different from that of India, although it is subject to the same drivers of energy security and climate change/pollution. Rather than a scramble to develop new sources of electricity generation, the UK is looking to maintain existing supply and increase the share of renewables in the energy mix. At the time of writing, and with the granting of Royal Assent to the Energy Act 2008, there is increased scope for gas importation and storage, carbon capture and storage and the development of new nuclear generation capacity. Within this, there is relatively little scope for the specific development of fuel cells and hydrogen, although there are a number of other sources of support for the sector from the UK government. The UK government's approach to supporting the fuel cell sector differs from that of many other European countries, where the approach is often to provide blanket funding for fuel cells, from R&D to commercialisation, with little or no involvement from the private sector. The UK, on the other hand, has a number of directed funding streams aimed at addressing specific aspects of the supply chain. The outcome of these is that the UK fuel cell sector is much more commercially-oriented than that of many other countries, with a significant number of start-up and spin-out (SME) companies listed publically, and a smaller number larger, corporate players. Many of the SMEs, including listed and private companies, have received VC, angel or other private funding. The sector in the UK is characterised by genuine pockets of industrial and commercial expertise throughout the supply chain from component manufacturers to systems integrators, with many successful fuel cell companies having originated as university spin-outs or start-ups.

In terms of government funding, there are a number of sources currently available for fuel cell funding. Leaving aside the European Fuel Cell and Hydrogen Joint Undertaking (FCH JU), fundamental and applied research tends to be funded by the Research Councils (e.g. the Engineering and Physical Sciences Research Council, EPSRC), with more commercially-oriented research being funded by the Carbon Trust and Technology Strategy Board, effectively independent executive agencies of the central government. The Carbon Trust's key focus is on the carbon saving potential of various technologies and funds innovation from R&D to demonstration, VC funding and full commercialisation. It is seen as a key partner by IP-sensitive innovators such as universities and spin-outs. Despite being independent from government and industry, the Carbon Trust has a strong track record of translating R&D to technologies that can help deliver particular on government policies. The Technology Strategy Board's (TSB) remit is wider than that of the Carbon Trust, covering various disciplines, and with a key focus on economic benefit for the UK. The TSB has an established reputation with the business sector and focuses strongly on networking and skills transfer (through its Knowledge Transfer Networks) and also has a role in encouraging increased R&D spending in the private sector. The Energy Technologies Institute, (ETI), opened in 2007, has a key focus on route to market, has a significant scale of funding available and has the potential to fund projects at 100% due to combined public/private funding. The ETI is industry-backed allowing access to management and engineering capabilities within industrial members and a direct route to market via these industrial members.

The following section gives an overview of selected UK organisations, their activities, and potential fits with Indian organisations. The matrices below are organised by position in the supply chain, i.e. R&D, component suppliers, systems integrators, etc. They are drawn from membership of the Low Carbon and Fuel Cell Knowledge Transfer Network (LCFC KTN www.fuelcellktn.com), however is not intended to be exhaustive. Overall, the UK contains some genuine pockets of industrial and commercial leadership at various points throughout the supply chain. The UK is home to a large number of start-up companies and SMEs companies and has arguably the most vibrant market for funding for fuel cell companies, including the VC, equity and AIM listed markets.

8.1 Research departments/organisations

The following section gives an overview of some of the highlights of fuel cell research in UK universities and research departments. Once again, it is not intended to be exhaustive but to give a flavour of what is currently being carried out in the UK. A study of UK capabilities in the area is currently being developed by the LCFC KTN and will be available in early 2009. A 'research atlas' conducted by the UK Energy Research Centre is currently available at: http://ukerc.rl.ac.uk/ERL0501.html

In contrast to India, where fuel cell research appears to be isolated and individual, the UK tends to have a consortium approach to much of the fuel cell sector, where RD&D and the market go hand in hand. The UK's arguably more 'joined up' approach has resulted in greater funding for the sector and a greater preponderance of (largely university start-up) SMEs in the fuel cell space, in contrast to India where the main companies operating in fuel cells tend to be large corporates with very few start-up or spin-out SMEs. An isolated approach to fuel cell research may benefit fundamental research, however in terms of 'value added' and potentially commercially useful research, a concerted joined up approach is more beneficial.

The following UK universities have active fuel cell and hydrogen research departments. Selected universities are discussed in more detail below.

- Birmingham University
- Cranfield University
- Imperial College London
- Keele University
- Leeds University
- Loughborough University
- Reading University
- Newcastle University
- Nottingham University
- St Andrews University
- Surrey University
- University College London
- Warwick University
- Southampton University

SUPERGEN consortium

The SUPERGEN Fuel Cells consortium is a consortium led by Imperial College and the Universities of Newcastle, Nottingham, and St. Andrews together with industrial partners Ceres Power, Rolls Royce Fuel Cell Systems, the Ministry of Defence Science and Technology Laboratory (DSTL) and Johnson Matthey. This group is tackling the challenges associated with making powerful, durable fuel cells. Working on three types of fuel cell technology, AFC, PEM, and SOFC the consortium considering how cells can run on a variety of fuels including anything from bio alcohol to diesel. The SUPERGEN Fuel Cells consortium is part of the wider Engineering and Physical Sciences Research Council (EPSRC) -funded SUPERGEN initiative.

The consortium's researchers are addressing the technical challenges of producing a thick-film solid oxide fuel cell with zero leakage, significantly improving fuel cell durability by halving the present degradation rate, substantially improving the power density of existing fuel cells, and improving fuel flexibility to cover renewable and logistic fuels. They have also established a dissemination, outreach and training programme in fuel cell science and engineering. Areas of investigation include polymer electrolyte fuel cells, fuels, solid oxide fuel cell anodes cathodes and electrolytes, novel routes to powders and components, characterisation techniques, fuel cell modeling, high temperature polymer electrolyte fuel cells, high temperature solid oxide fuel cells, metal supported intermediate temperature solid oxide fuel cells, and military applications for fuel cells.

University of Birmingham

The University of Birmingham has a well-established fuel cell research group encompassing the departments of Chemical Engineering, Metallurgy and Materials, Chemistry, Biosciences. The University has four main capabilities: hydrogen production; hydrogen storage; hydrogen utilisation (i.e. fuel cells); and hydrogen and the fuel cell economy. The University has particular strengths in SOFC for use in domestic CHP applications (the reduction of temperature and redox-related degradation of SOFC components) and PEM fuel cells for use in transport applications (specifically the establishment of supply chains and MEA development. One of the research groups active at Birmingham focuses on the bio-production of clean hydrogen from sugar-rich waste products – a potential synergy with Indian organisation looking to develop bio-waste feedstocks for fuel cells. The university specialises in the discovery and characterisation of solid state hydrogen storage materials including magnesium alloys, complex hydrides, graphite and porous solids; the development of novel thin-film palladium alloys for hydrogen purification; and the development of hydrogen energy related demonstrator projects. The university opened one of the first hydrogen refuelling stations in England in 2008, and runs a fleet of fuel cell powered 'Microcabs' as well as a fuel cell powered canal boat.

Imperial College

Imperial College boasts the largest academic fuel cell program in the UK with activity in fuel cells for over 30 years. Research focuses on PEM, DMFC and SOFC electrolytes, from material characterisation of SOFC to reactant transport in PEMs, but also includes AFC systems. Work is conducted across a wide range of departments from Chemistry and Chemical Engineering to Materials and Mechanical Engineering, and includes atomistic modelling of ion conductors, stress-strain analysis of SOFCs in dynamic loading, mesoporous and nanostructured PEM and DMFC catalysts, in-situ measurements, fuel processing, systems integration and hybridisation, anode and cathode materials discovery and characterisation, and economic, environmental and policy modelling. A spin-out company, aim-listed SOFC developer Ceres Power, came out of Imperial's SOFC work. The College's fuel cell team has recently made headlines with its entry in the inaugural season of the 'Formula Zero' championship – a fuel cell powered go-kart racing championship that Racing Green, Imperial's team, has had notable successes in. More information and links can be found at the Imperial College Fuel Cell Network website: http://www3.imperial.ac.uk/fuelcells

University of Loughborough

The Centre for Renewable Energy Systems Technology undertakes research and teaches postgraduate degree courses in sustainable energy technologies. It currently has a team of researchers working on a field trial project incorporating electrolysis from renewable energy sources, hydride and pressurised hydrogen storage (in collaboration with Birmingham University) plus stationary and vehicular PEM fuel cells. The university has strong links with India through the Maini Group, who are developing a fuel cell version of their electric vehicle with researchers from Loughborough. This university also opened a hydrogen refuelling station in 2008. The university has a strong tradition of automotive engineering, benefitting from its location in the English midlands, close to a number of fuel cell companies such as Intelligent Energy and Rolls Royce Fuel Cell Systems. Loughborough also hosts Cenex, the Centre of Excellence for Low Carbon Technology as well as the newly opened UK Energy Technologies Institute (ETI).

8.2 Component manufacturers

The following sections summarise UK companies who are active in specific parts of the supply chain. This list is not intended to be exhaustive and further information can be obtained from the UK Organisation Search Facility or by emailing moderator@fuelcelltoday.com

NAME	ORIGIN/TECHNOLOGY/ BUSINESS AREA
Bac2 Conductive Composites	Start-up. Bipolar plates using novel materials science.
CMR Fuel Cells	Start-up. DMFC component and stack manufacturer.
Dek Printing Machines	Corporate. Substrates and membrane printing technology.
Johnson Matthey Fuel Cells	Corporate. PEM and PAFC component manufacture.
Oxford Catalysts	University spin-out. Hydrogen-on-demand
Ilika	University spin-out. Materials research.
QinetiQ	Former government agency, now privately owned. Has programmes developing materials for PEMFC, DMFC and SOFC, stacks, systems integration and reforming.

8.3 Stack manufacturers

NAME	ORIGIN/TECHNOLOGY/ BUSINESS AREA
Acal Energy	Spin-out. Platinum-free electrode technology.
Adelan	Spin-out. Small-scale tubular SOFC
Ceramic Fuel Cells Limited (CFCL)	Start-up. Residential SOFC CHP developer, tie-in with utilities.
Ceres Power	Spin-out. Residential SOFC CHP developer, tie-in with utilities.
CMR Fuel Cells	Start-up. DMFC component and stack manufacturer.
Intelligent Energy	Spin-out. Stack; system; fuel processing.

	Product Stack: 1-75kW PEM unit.
Rolls Royce Fuel Cell Systems	Corporate. SOFC manufacturer of 'power plant' (100s kW – MW) scale.
St. Andrew's Fuel Cells.	Spin-out. Tubular SOFC technology.
Voller Energy	Start-up. Portable PEM systems integrator.

8.4 Systems integrators/consultants

NAME	ORIGIN/TECHNOLOGY/ BUSINESS AREA
Auriga Energy	System integrator and control system developer working with the University of Bristol.
Bryte Energy	Consultancy services relating to the design, implementation and operation of hydrogen and renewable energy systems.
Element Energy	Engineering consultancy with emphasis on fuel cells
Logan Energy	Systems integrator with experience of installing SOFC and PEM units in buildings
E4tech	Business consulting company, focusing on novel energy technology, strong track record in hydrogen and fuel cell industry
Valeswood	Small company, assembles fuel cell bicycles from components made in China and Finland

8.5 Adopters/enablers

NAME	TECHNOLOGY/ BUSINESS AREA
CoreTech Ventures	Small VC and advisory company, highly focused on fuel cell techs
Conduit Ventures	VC company focused on fuel cells and hydrogen, with investors including Shell Hydrogen, Johnson Matthey and Mitsubishi Corporation and investments worldwide
Black Country Housing Association	Innovative Housing Association with experience of installing and running fuel cells in residential applications and at the University of Birmingham.
LHP/TfL	Transport for London's hydrogen vehicle project will see 60 H2 fuel cell and ICE vehicles on London's roads by 2010.
Pure/Unst	Hydrogen/Fuel cell/Renewable research centre in the Shetlands. Innovative hydrogen community project.
UPS Systems	Fuel cell in UPS Systems office (UPS the fuel cell company, not the delivery company!).
Woking Borough Council	Installed 200 kWe fuel cell on private wires, groundbreaking project for the UK.

9. Potential synergies with the UK

There are a number of areas where UK and Indian organisations might find common ground to work together. As two nations with a shared history, common language and similar academic, commercial and political institutions, the UK and India have a long-standing set of synergistic relationships between research and industry. Most notably, some of Britain's most iconic brands (including Tetley tea and Jaguar and Land Rover cars) are now owned by Indian companies and collaborations between the UK and India are growing. The following analysis does not intend to be exhaustive, nor prescriptive, on the potential synergies in the fuel cell sector between the two countries. Rather, it intends to identify a number of 'fits and 'gaps' on both sides which may be explored by further collaboration. A further potential collaboration is with UK venture capital companies, which have traditionally focused on India's ICT sector and more traditional clean technology sector (i.e. wind and solar) but may in future choose to invest in the growing fuel cell sector.

9.1 Research

In the area of fundamental fuel cell research, there are some areas of deep expertise, particularly on the chemistry and catalysis of low temperature membranes (PEM and DMFC). Much of this research is being done in the various branches of the Indian Institute of Technology, with some growing expertise (on SOFCs in particular) from corporate research centres such as Tata and Reliance Industries. As noted above, not all of this research is co-ordinated nationally leading to a somewhat patchy R&D landscape. However, in many cases, chemistry and engineering departments of IIT working on fuel cells collaborate with other campuses, universities and departments in India and internationally on an informal basis, leading to well-respected academic publications and a good deal of grant funded research. University departments are often looking out for international collaborative opportunities, particularly with companies who can co-fund research projects. Although several campuses of IIT now have business development units which aim to commercialise certain technologies, many universities in India tend not to have such business units and are focused on purely fundamental research without formal mechanisms for technology transfer and commercialisation.

An interesting dynamic operates between India's research institutes, government and the commercial sector. The academic sector is traditionally strong and has historical access and influence with government departments, which enables it to explain the case for funding of specific areas of research within hydrogen and fuel cells, for example. The relationship between academia and industry is less strong, and that between government and the fuel cell industry hard to quantify, as the industry is limited. In some instances the communication of research and development needs may therefore be skewed towards particular areas of research that are important and novel but not directly applicable to near-term introduction of fuel cells. Industry is not generally prepared to invest in fuel cell technology unless it sees a clear commercial benefit, so it appears as if a gap exists for the more applied research and development that completes the spectrum between blue-sky thinking and applications engineering. Some organisations such as CFCT, follow a different model, not practised in the UK, where they might pay an Indian SME to collaborate on fuel cell projects and receives a small return on sales if the project is successful. This is aimed more at commercialising the technology than revenue-raising. There are therefore some clear gaps between the work of different research institutes, the government and the private sector, gaps which could potentially be filled by collaboration with UK organisations. There are therefore some clear gaps between the work of different research institutes, the government and the private sector, gaps which could potentially be filled by collaboration with UK organisations.

International academic collaborations are welcomed by most Indian research organisations, drawing on those which are already established. India, like the UK, has genuine pockets of research expertise, for example in solid state chemistry, and it appears that value could be added to both countries' research organisations by further collaboration. A number of organisations which are active in the 'private' sector also have crossover activities in the research sector. These are dealt with in the section on commercial activity. The fuel cell situation in India is becoming more coherent that it has apparently been in the past, offering opportunities for enhanced collaboration nationally and internationally, and potentially more rapid advancement than in the past. However, many researchers in the Indian fuel cell research sector come from individual disciplines and have no particular 'fuel cell' perspective, which has proven essential in other countries for successful integration and development. Similarly, industry does not necessarily contain fuel cell experts and hence there is a need for some co-ordination and wider awareness-raising. This may be also be true of the Indian government which has branches, for example the transport department and the military, who could be significant early market fuel cell adopters.

The following section looks at certain Indian universities and potential opportunities to work with UK organisations based on interviews conducted in August 2008. It should be noted here that in October 2008, Research Councils UK (RCUK) launched their office in New Delhi which is aimed at strengthening research collaboration between Indian and UK universities.

Central Electrochemical Research Institute (CECRI) – As described above, CECRI's interests lie in developing catalytic components, membranes, designs, and stack deigns for PEM and DMFC. CECRI are actively looking for industrial partners from whom to license technology and commercialise it in India, working on barrier issues such as reducing the cost of components and manufacturing. The Institute already has some contacts with international fuel cell companies such as Plug Power and also systems integrators and adopters such as the UK's QinetiQ.

Central Gas and Ceramic Research Institute (CGCRI) – In addition to CGCRI's work with BHEL on developing SOFC technology for stationary applications running on various fuels, the Institute has collaborated in the past with Japan. The possibility remains that CGCRI may work with UK institutions, such as Imperial College, on developing biogas feedstocks for its 1-5 kW units for remote distributed power. Given CGCRI's expertise in ceramic powders, there is also the possibility of working with UK-based developers of SOFC, such as Ceramic Fuel Cells Limited. CGCRI has an ongoing interaction with Germany, including an annual Indo-German workshop alternating between Germany and India.

Centre for Fuel Cell Technology (CFCT) – CFCT's multi-disciplinary research on materials, membranes, catalysts, and bipolar plates builds on collaborations between different institutes already carrying out similar work. For example, CFCT is building on existing research with NCL on catalysis, BHEL on balance of plant and SPIC-SF on stacks. Furthermore, CFCT is working with Mahindra on integrating fuel cell systems into vehicles and also with the IITs on developing novel bio- and chemical-production of hydrogen. CFCT is actively looking for collaborative industrial partners on electrode developments as well as various industrial partners (specifically from the chlor-alkali industry) on large-scale hydrogen production.

IIT Bombay – A range of research in which IIT Bombay is engaged (hydrogen generation and storage, catalysis, DMFC, SOFC) lends itself to commercial applications. IITB has a business unit which aims to commercialise promising technologies, and could be argued to be more business orientated than other universities. The range of high temperature fuel cell work being carried out at IITB has a potential fit with stationary backup power and mCHP applications in India and the organisation is open to collaborations in this area through its nascent Fuel Cell and Hydrogen Centre. Similarly, the UK has a range of university spin-out SOFC companies such as Ceres Power and St. Andrews Fuel Cells with interests in natural gas powered mCHP.

IIT Delhi – Similar to IITB, IITD has a strong research base mainly looking at the fundamentals of fuel cells for portable electronics and backup power applications. Like IITB, IITD has an innovation centre aimed at commercialising technologies and IP coming out of the university. IITD has a good record of international collaborations, including being part of a UK Engineering and Physical Sciences Research Council consortium, and having links with US-based SOFC UPS developer, Bloom Energy.

IIT Madras – At present, IITM is collaborating with a number of other IITs on its key area of research: conducting polymers to replace conventional fuel cell membranes. IITM does not currently have any on-going collaborations with industry in this area, although there is clearly considerable scope for developing this technology with developers of end-use devices such as DMFC replacements for battery-powered portable electronic equipment. A number of UK companies are working on similar technologies, such as CMR Fuel Cells (small-scale fuel cell systems) and Bac2 (electro-conductive polymers).

National Centre for Catalysis Research (NCR) - has strong research capabilities in DMFC membranes and catalysis and, as noted above, is engaged with developing a non-fluorocarbon based membrane for manufacture in India. NCR is currently working with a range of other institutes in India and, although the Centre has collaborations with institutes in five other countries, there is currently no ongoing overseas collaboration on fuel cells. However, as a newly developed centre, the intention is to develop international links further.

TERI – TERI have a long history of collaboration with the Indian government, as well as overseas organisations. Although relatively little is going on at present on fuel cells and hydrogen, TERI is open to international partnerships on developing fuel cells in India in line with the NHER.

9.2 Commercial activity

Many Indian companies, particularly the public-private entities such as BHEL and the larger conglomerates such as Reliance and Tata, have established fuel cell research programmes to create future business opportunities. In addition to working with Indian and international research organisations as part of these programmes, a number of companies are looking to develop more commercially orientated collaborations with a range of international partners. The following section describes some of these.

BHEL – As the principal supplier of power generation equipment in India, and a partly state-owned entity, BHEL is looking to develop international collaborations particularly on fuel cell technology that utilises waste hydrogen generated from the chlor-alkali industry. BHEL has interests in captive power as part of grid strengthening work it is carrying out with a view to providing ‘electricity for all’, one of the Indian government’s key commitments.

Mahindra – Mahindra have launched their low-cost range of SUVs in a range of markets, including the UK and wish to grow in this market. Given that they intend to develop hydrogen, fuel cell and other alternative vehicles in the near future, a range of UK component manufacture, systems integration and balance of plant companies could collaborate in this work.

Reva – Reva have an established market for their electric city vehicles in London, their biggest single market. They have indicated that they consider the UK to be a key early market for demonstration of a second-generation version of their fuel cell vehicle. They are already working with Loughborough University and great potential exists for a UK-India collaborative demonstration programme.

Tata - As a large conglomerate, Tata has interests in a range of stationary and transport applications of fuel cells. It is in stationary fuel cells that some of the most visible international collaborations have been seen to date – such as the recent announcement that Plug Power and Tata Telepower has demonstrated a fuel cell backup power unit.

Tata Motor has ongoing collaboration with Coventry University in the UK and, through its acquisition of Jaguar-Land Rover recently strengthened its ties with British industry. Tata Motor's fuel cell programme is focusing initially on the bus demonstration project in time for the 2010 Commonwealth Games. This showcase opportunity also offers the potential for further early market deployments. Tata have identified the following areas with which it wishes to collaborate with both domestic and international organisations:

- Modelling of hydrogen and air modules
- Modelling of Fuel cell system
- Development of fuel cell control system
- Modelling of batteries
- Modelling of ultracapacitors management System
- Development of Battery management System
- Modelling of motor and controller (as part of electric traction)
- Modelling of power train and sizing aggregates of power train

- Development of cooling system for fuel cells stacks and electric machines
- Development of algorithms for onboard hydrogen management system for vehicles
- Design of bus system architecture for vehicle control, power-flow management
- and energy management
- Design of fuel cell control system ECU
- Design of bus management system and controller area network

9.3 Potential areas of collaboration

In discussions with various players in the industry, certain issues such as production and manufacturing of fuel cells, the development of a supply chain, and international collaboration emerged. A webinar held between the Indian and the UK fuel cell industries in November 2008 elaborated on some of these issues, and raised other potential areas of collaboration also during discussions. Some of these could be seen as challenges to the industry, but are also potential opportunities if addressed early on and build on the strengths between India and the UK. These are discussed below:

Supply chain building - emerging from the discussions between UK and Indian industry was the need to build capacity in terms of fuel cell manufacturing. Key to this is to bring together the different elements of the supply chain in both the UK and India, playing to the respective strengths of the two countries – e.g. turning R&D projects into commercial products; high volume, low cost component manufacturing; systems integration for the particular set of operational characteristics of the Indian market, cost reduction through joint collaboration. A key message from the discussions coming out of the webinar was that a value proposition must first be established for particular early market applications (e.g. backup power), then project partners need to be identified and brought into the supply chain. Crucial in all of this is communication between all of the project partners, which means effective establishment of consortia.

Consortium building – there is a substantial appetite for collaboration between both countries, throughout the supply chain from R&D to systems integration. A greater focus on communicating the capabilities and needs of the fuel cell community in both countries is something that this report and the recent webinar aims to initiate. Further work between the LFCF KTN, SIN and UKTI aims to build on this dialogue. In terms of specific consortia, a relatively 'easy win' is for greater communication between R&D organisations in both India and the UK, a process that has already begun in some jointly funded projects and some India-wide discussion fora. The wide variety of funding now becoming available for fuel cells through, for example the EU Joint Technology Initiative (JTI) opens up the possibility of joint funding for RD&D project. Another is to bring together the industry to look at 'barrier' issues such as skills gaps, codes and standards, and consumer acceptance. A third is to focus on key application areas, such as stationary fuel cells for backup power and help to develop a supply chain, bringing together component manufacturers who may be new to the fuel cell industry. Overall, more information circulation is required between industry and government and between the two countries. Although commercialisation of fuel cells has begun in some niche early markets, joint studies need to be carried out now between the two countries in order to develop fuel cells and associated infrastructure for longer term markets such as light duty and heavy duty vehicles. With such consortia and paper studies targeting early and longer term markets, with the right finance and funding, implementation can begin.

Joint project funding and financing – in bringing together consortia to jointly develop fuel cells, a gap has been identified to jointly fund projects between the two countries.

Aspects of the fuel cell industry requiring funding in both countries have been identified as:

- Implementation of demonstration programmes
- Subsidy for products
- Tax incentives to industry & consumers
- Targeted funding for pre-competitive technologies

Government departments and agencies in both countries (NHEB and DST in India, research councils, Carbon Trust and Technology Strategy Board in the UK) are already beginning to providing funding for some of these. They may be instrumental in providing funding for such projects being done on a joint basis, particularly where there is very clearly a 'value added' for both countries. Furthermore, some super-national funding mechanisms such as the Fuel Cell and Hydrogen JTI contain provision for joint projects with developing countries who are signatories to the IPHE, assuming there is match funding available from the partner country.

Aside from government funding, there is considerable scope for private sector financing of joint projects in the two countries. Indeed this may have more potential for immediate success given the considerable scope for fuel cell adoption in India in the near future. The large, vertically integrated corporate players in Indian industry are able to directly fund their technology acquisitions and joint ventures. Smaller players may need to go to the public markets, private equity or VC funders to raise finance for investment in new fuel cell technology or manufacturing facilities. Given that certain players in the UK finance sector have considerable expertise in financing and brokering fuel cell deals, particularly those where there is a UK partner involved, there is clearly an opportunity for collaboration where Indian organisations are looking to private financing for the development of fuel cell technology.

Fuel availability – the cost of production, distribution and storage of hydrogen is a challenge in any market, and but is crucial in the very price-sensitive market of India. It is for this reason that the early market applications of fuel cells in India (such as telecoms backup power) appear to be focusing on using reformed natural gas. Thus there is an immediate opportunity for manufacturers of reformers (who are relatively few in number worldwide). Longer term, liquid fuels may also be developed for small-scale backup power applications, leading to a further opportunity for reformers and also potentially for small scale DMFC technology. Ultimately, production of 'off-grid' hydrogen from sustainable sources is a goal (as enshrined in the NHER), and clearly there is a large potential opportunity to develop low-cost electrolysers for the Indian market, as well as the power electronics that will enable wind and solar generating equipment to be integrated with fuel cells. In addition, there is considerable scope for the development of novel reformers for e.g. biomass feedstocks. India has a history of developing biomass energy resources for its large rural population. Developing reformers and fuel cells that run on biomass is clearly a good fit for electrifying rural communities, and is an area of potential co-operation between UK component and systems manufacturers and potential end-users.

Safety and awareness – stemming from discussions at the November webinar, codes and standards surrounding the use of hydrogen emerged as a key barrier issue to the fuel cell industries both in India and the UK. In terms of safety, hydrogen is currently regulated by the Chief Controller of Explosives in India and the Explosion Safety Section of the Health and Safety Executive in the UK. Although hydrogen is widely used as an industrial gas in both countries, lack of regulatory awareness of its use in fuel cells means that a number of barriers exist to, for example, putting in place a hydrogen refuelling system or using hydrogen fuel cells in buildings. Both countries could benefit from synergistically developing common regulatory mechanisms for the approval of hydrogen in fuel cells for various applications. Common regulatory mechanisms for the approval of other fuels such as methanol could also be developed. In terms of certification for new fuel cell products, India is clearly leading the way in terms of stationary fuel cell deployments and commonalities in the certification process between India and the UK could be developed.

Skill of integration in India – it is often said that India and its people work best under pressure. Under the pressure of an accelerating economy, a growing power shortage and energy security and environmental challenges, India certainly appears to be working best in the fuel cell sector – with the biggest fuel cell unit deployment to date agreed for the next 3-4 years by Acme, IdaTech and Ballard. The sheer size of the market for backup power in India means that the country may spring any number of surprises in terms of scaling up manufacturing capacity to meet domestic demand and potentially also in exporting manufactured fuel cell systems. India has a large number of small-scale component suppliers specialising in low cost manufacturing of key fuel cell components such as pumps, blowers, and valves (key balance of plant components). This low-cost manufacturing will undoubtedly help achieve the economies of scale required to reduce the cost of fuel cells. Acme, IdaTech and Ballard have realised this, and will be manufacturing their units together with these very component suppliers, ultimately both for the domestic and the export market. A huge potential opportunity exists for UK companies to source low-cost components from India to help bring down the cost of fuel cell units.

History of e.g. advanced battery technology – Although India has a number of skills in terms of technology development, there are a number of areas where the country does not have a skills base, such as in the development of advanced energy storage technology. However, as described above, India is adept at taking the best available technology worldwide (through buying, licensing and joint ventures with foreign firms) then adapting it for its own purposes – such as reducing cost and improving durability. Mahindra's development of a battery hybrid SUV characterises this – the company did not develop the battery technology in-house but rather bought it from abroad, then did the systems integration with its own drivetrain in-house and then looked to modify key parameters using Indian expertise (improving performance, reducing cost). A similar pattern will undoubtedly emerge in the fuel cell sector – Indian firms are actively seeking out the best available fuel cell technology and wish to adapt and manufacture it on a systems scale in India. The UK, home to key stack component manufacturers, should seek to benefit from Indian companies who wish to use the best of foreign technology and place itself at the heart of the supply chain.

Affordability – Fuel cells are generally more expensive than incumbent technologies in a variety of countries around the world. There therefore needs to be a very clear value proposition for fuel cells to be adopted, one that emphasises operational characteristics over capital cost. There is considerable scope for cost reduction with the advent of low-cost, high volume manufacturing in India. However, the question remains, why would India adopt fuel cells first even as they remain unaffordable in many western countries? The answer lies in the need for reliable power, any power for a range of applications, and the operational costs of fuel cells may be ultimately lower than those of incumbent technologies such as diesel generators, especially in long run-time environments. The unique set of circumstances of the Indian energy landscape makes fuel cells a better fit in the immediate term than in many established markets.

National fuel cell research priority areas – despite the NHER, and the funding for fuel cell research coming from the DST and MNRE, there is still a lack of national fuel cell research priority areas. Although individual institutes have their own set of research priority areas, there is no real co-ordination of these activities at national level. This may change in future with the opening of the National Hydrogen Energy & Fuel cell centre, and also as calls for a national fuel cell network are heeded. India has a set of world-leading fuel cell researchers. With better co-ordination and more international collaboration (not least with the UK, with which some of the IITs already have ongoing projects) it has the potential to be world-beating.

10. Conclusions

Based on the outcomes of this report and wider discussion with the Indian and UK fuel cell industries, it is clear that:

- India has a serious lack of electricity generation capacity. This is a factor that dominates discussion of India's energy landscape, exacerbates all other energy security issues and has led to recent geo-political developments such as the recent Indo-US nuclear deal. Diversification of energy generation methods is not simply an energy security issue in other words, to move away from over-reliance on a small number of energy sources, but also is a way of increasing energy generation capacity more quickly. The huge demand for electricity in India is creating the opportunity for a wide variety of new energy generation technologies including fuel cells.
- The sheer size of the country and the current lack of grid infrastructure is creating opportunities for distributed energy production methods. The fact that electricity theft from the grid is a real problem in India means that opportunities are being created for methods of production that are distributed and without long and therefore vulnerable supply lines.
- The imminent commercial take-off of fuel cells for distributed generation has implications for unit cost reduction, particularly component manufacturing and systems assembly both in the Indian market and in other overseas markets.
- There is a relative paucity of passenger vehicles as a proportion of the population and, by implication, there is a huge untapped market for primarily light duty vehicles. This latent demand must be couched against the already severe urban air quality problems, meaning that there is a huge potential market for clean vehicles.
- The transport sector in India shows promise for buses and 2- and 3- wheeled vehicles, albeit in the longer term. This makes it imperative to begin to build consortia and supply chains now, particularly relating to hydrogen infrastructure, and start to address some of the barrier issues, including codes and standards, technology readiness and affordability.
- India has a strong university research sector with notable highlights in fuel cell and hydrogen technology. This research sector is increasingly open to international collaboration.
- The Indian government is facilitating fuel cell and hydrogen RD&D through the National Hydrogen Energy Board as well as other groups and programmes.

- The approach of Indian companies in the private sector is increasingly to buy or licensing the best technology available worldwide then adapt it for the Indian market, with a view to establish an indigenous manufacturing base.
- The UK contains genuine pockets of commercial and industrial leadership throughout the fuel cell supply chain, with fuel cell start-up and corporate entities that are arguably more commercially focused than their counterparts in other parts of the world. Like Indian companies, they are outward-looking and open to international collaboration.
- The two countries, with a shared history and strong cultural and commercial ties, would benefit from greater collaboration in the fuel cell sector. This report has identified a number of collaborative opportunities, building on the strengths of the respective fuel cell industries, and also identified a number of outstanding challenges which remain to be addressed.

11. Future directions

Based on the findings of this report, as well as a webinar held between the UK and Indian fuel cell industries in November 2008, the authors suggest the following areas to follow up in order to build future collaborations between the UK and India in the fuel cell sector.

- **Supply chain and consortium building –** through further interactions and engagements, focusing on specific technology and application areas and bringing together a range of project partners as well as organisations new to the fuel cell industry (such as component manufacturers). The UK and India have a range of systems integrators and component manufacturers who may benefit from the synergies of working together.
- **Focus on joint demonstration projects and joint funding -** through upcoming opportunities such as the EU Joint Technology Initiative and future tranches of funding being made available from the Carbon Trust and Technology Strategy Board (UK) and NHEB (India). Explore match funding opportunities for technology demonstration and deployment.
- **Explore private sector funding opportunities –** particularly those that involve funding for early market applications such as backup and uninterruptible power.

This should be done in parallel with building the supply chain. The UK has been a traditional centre for clean technology, and particularly fuel cell, financing.

- **Component manufacturing –** The UK and India may benefit from jointly procuring fuel cell balance of plant from the large number of small-scale component suppliers specialising in low cost manufacturing in India. This low-cost manufacturing will undoubtedly help achieve the economies of scale required to reduce the cost of fuel cells
- **Partnerships on hydrogen reforming and electrolysis** – one of the key issues in India at present is fuel availability – which could come from reforming natural gas and other feedstocks, or from electrolysis. Both are potential areas of collaboration with UK industry.
- **Codes, standards and certification –** are challenges for both India and the UK to address. Both could benefit from developing common codes, standards and certification procedures, particularly relating to hydrogen infrastructure.
- **International network on fuel cells** - several key stakeholders have commented on the need for an UK-India network on fuel cells and hydrogen to communicate research, commercial and technical developments as well as developments related to cost, manufacturing and government policy. There is a great deal of expertise in the fuel cells sector in both countries and with greater co-ordination of activities and international collaboration, there is the potential for considerable advances in the fuel cell sector of both countries, with attendant advantages for both countries' shared goals of economic growth, energy security, and pollution reduction.