Executive Summary

Innovation in energy technology has widespread implications for OECD economies. Although the energy sector accounts for a small share of GDP, the pervasive use of energy throughout modern economies makes uninterrupted supplies and stable prices critical to sustaining growth. Rapid growth in energy demand coupled with growing concerns about energy security and the environment, however, raise questions about the sustainability of the current energy system and call for renewed efforts to develop and deploy new and improved energy technologies that can support a sustainable energy system.[1] Understanding how to stimulate innovation in energy technology is therefore of growing importance.

This report summarises the conclusions of a project on innovation in energy technology organised by the OECD Working Party on Innovation and Technology Policy. It forms part of a larger effort to compare innovation processes in different industry sectors to both provide guidance to policy makers on development of innovation policy and to more fully elaborate the national innovation systems approach to policy making. The report focuses primarily on innovation in hydrogen fuel cell technology, which was the subject of country studies prepared by experts from nine countries: Canada, France, Germany, Italy, Japan, Korea, Norway, the United Kingdom and the United States. It also addresses innovation in oil and gas technologies, drawing on work done in France, Norway and the United States, which allows some ability for comparative analysis across national innovation systems and among innovation systems for different energy technologies.

Innovation in hydrogen fuel cells

Hydrogen fuel cells are a revolutionary technology that promises to transform the global energy economy, as they offer long-term potential for high-efficiency with near-zero emissions of greenhouse gases. With potential applications in transportation, power generation and portable power, the market for fuel cells and related products, according to some estimates, is projected to reach USD 29 billion by 2011, and could reach as high as USD 1.7 trillion by 2021. Hydrogen fuel cell technology is complex, however, and numerous technical and economic problems remain to be solved, particularly in automotive applications, before it can achieve widespread deployment. In addition, the commercial success of hydrogen fuel cells requires that suitable infrastructure be developed for the generation, distribution and storage of hydrogen fuels. Fuel cells must prove their ability not only to generate sufficient power for a range of envisioned applications with different performance and cost requirements, but also to do so more effectively than existing and emerging energy technologies (*e.g.* internal combustion engines, batteries and renewable energy sources), many of which have benefited from decades or more of continual refinement.

1. International Energy Agency (IEA) (2004), *World Energy Outlook 2004*.

Multiple factors drive innovation

While improvement in environmental quality in general and concerns about climate change in particular are important drivers of the fuel cell innovation system for all countries, other factors also motivate innovation. The economic opportunities presented by hydrogen fuel cells are a powerful driver for those countries with large automobile manufacturing sectors, including France, Germany, Japan and the United States, as well as for a country such as Norway that desires to make better use of existing energy resources. For countries with limited domestic energy resources that depend heavily on imported oil for transportation, including Japan, Korea and the United States, energy security is an equally strong driver of the fuel cell innovation system. Fuel cell innovation in Canada, Norway and the United Kingdom, with large domestic energy resources, and in countries with intermediate levels of resources, such as France, often takes the form of a “fast-follower” strategy, although a cluster of Canadian firms has emerged as industry leaders in fuel cell technology.

Government and industry contribute to energy R&D funding

Both government and industry invest considerable sums in fuel cell R&D. Although the balance between these two sources of funding varies considerably among countries, the share financed by the public sector is relatively high, reflecting the large public interest in successful commercialisation of fuel cells. The US government announced in 2003 its plan to spend USD 1.7 billion over the next five years on fuel cell R&D including hydrogen production, storage and infrastructure. Japanese government spending on fuel cell R&D reached USD 320 million in 2004. The European Community announced plans to spend USD 2.1 billion between 2003 and 2006 on renewable energy, mostly on hydrogen fuel cells.

With the potential commercial applications of fuel cells becoming more apparent, industry is playing an increasingly important role, investing more in fuel cell R&D than governments in many countries. Current annual spending by the private sector on hydrogen fuel cell R&D worldwide is estimated to be about USD 1 billion. Industry R&D spending in the United States peaked at over USD 1 billion in 2000, although it declined to about half that level in 2004, reflecting weaker economic conditions at the turn of the millennium. Venture capital firms have played a limited role in funding fuel cell start-up firms because fuel cell technology is highly capital intensive with long time horizons for commercialisation; and public policy and regulatory regimes regarding fuel cells are not well developed, increasing uncertainties about future market conditions.

National innovation systems for fuel cells are complex and diverse

Because of their wide range of applications, fuel cell innovation systems engage a diverse and changing set of actors in public and private sector R&D and other innovative activities. Government laboratories and universities are important players in generating and diffusing knowledge. While universities generally account for the majority of scientific publications, government laboratories also play an important role in fuel cell technology, reflecting longstanding traditions of energy research in many countries and the significant societal benefits expected to result from deployment of fuel cell technology. The work of these public research organisations (PROs) is funded (and performed) by many government ministries, including those with responsibility for research, industry, energy, environment and defence, reflecting the range of interests in fuel cell technology. Industry is heavily engaged in innovation of hydrogen fuel cells. Active firms include large national and multinational enterprises, as well as small and medium-sized enterprises (SMEs). While SMEs tend to focus specifically on development of fuel cells, large firms operate in a number of industry sectors, including energy, automobiles, electronics and chemicals. These firms are connected in complex ways by organisational networks that generate, diffuse and use knowledge.

The balance between the public and private sectors in fuel cell innovation varies considerably from one country to another, reflecting different public sector motivations for promoting development of fuel cells and different industrial structures. In Italy, most fuel cell activity takes place in the public sector, although industry interest is growing; in Korea, government funding exceeds estimated funding from industry. In other countries, most notably Canada and Japan, most fuel cell knowledge resides in industry, as opposed to PROs, but the public sector role is increasing. Public and private financing of fuel cell R&D are approximately equal in France, and several other countries, including Germany, Japan and the United States, appear to have motivated both public and private sector involvement in fuel cells.

Public/private partnerships (P/PPs) are common vehicles used by nearly all countries to spur fuel cell innovation and encourage knowledge sharing. Most P/PPs engage researchers from public and private-sector organisation who work on commonly identified objectives and share costs. The partnerships help governments identify R&D gaps and opportunities as well as technical barriers to be removed, and enable industry to share risks of investing in pre-commercial technology. France's PACo network, Germany's Futures Investment Programme (ZIP), Japan's Hydrogen & Fuel Cell Demonstration Project (JHFC), and the US FreedomCAR initiatives are some examples. These partnerships have blurred the traditional line between the roles of government performing basic research, and industry performing applied R&D.

Despite the nascent stage of development of fuel cell technology, innovation activities are surprisingly globalised. Firms try to leverage their R&D resources by entering into strategic alliances with key customers, suppliers, and research organisations in foreign countries. For example, Ballard Power Systems, headquartered in Canada, has developed an extensive international R&D system including establishing R&D facilities in Germany. Both US and Japanese automobile manufacturers also have developed extensive, global networks of R&D collaborators. At the government level, several initiatives have been implemented to improve international co-ordination of research, development and commercialisation. The International Partnership for the Hydrogen Economy (IPHE), established in 2003, involves more than a dozen countries accounting for 85% of global GDP, with the goal to help co-ordinate and leverage on-going R&D activities to accelerate hydrogen fuel cells. Within Europe, the H_2 and Fuel Cells Technology Platform has been set up to integrate the existing, dispersed national R&D programmes in order to improve co-ordination and effectiveness.

Fuel cell innovation policy extends beyond R&D

Successful innovation in fuel cells requires much more than R&D. Market development is extremely important as fuel cells represent a novel approach to satisfying energy needs in application areas served by a number of entrenched technologies. The costs and risks of switching to fuel cells are high, and customers may be understandably reluctant to invest in fuel cells until they are more fully convinced of their capabilities and reliability. Fuel cell innovation programmes, as many energy innovation programmes, tend therefore to aim not just at promoting R&D, but at encouraging a fuller spectrum of activities commonly referred to as RDD&D – research, development, demonstration and deployment. The demonstration and deployment components of this approach aim to test fuel cell technology in operational settings to illustrate their capabilities, identify infrastructural needs and gain operational experience that can lead to successful market entry.

Governments have taken a number of steps to support demonstration and deployment, often in collaboration with industry. Some countries subsidise deployment of fuel cells, via co-financing of purchases (as in Norway) or tax incentives. In the United States, the state of California has taken a regulatory approach, implementing a requirement for zero-emission vehicles that is intended to stimulate manufacture and purchase of vehicles using fuel cells and other alternative energy sources. Countries also support demonstration programmes. The US government has invested in a test fleet of 50 fuel cell-powered vehicles and refuelling stations, and the governments of Germany, Japan and Korea have also supported demonstrations of automotive and stationary applications. Canada is supporting three major large-scale, multi-stakeholder demonstration projects that will accelerate the transition to a hydrogen economy. The BC Hydrogen™, the Hydrogen Village™, and the Vancouver Fuel Cell Vehicle Program will demonstrate and evaluate the integration of a number of hydrogen and fuel cell technologies across Canada. Project stakeholders in these and other initiatives include federal, provincial and municipal governments, industry and academia.

Policy can affect other elements of the innovation system as well. The creation of regional, national and international programmes for hydrogen fuel cells plays a catalytic role in engaging the diverse set of actors in the innovation system. They can help create a common vision that minimises uncertainties as technologies are advanced toward commercialisation and complementary investments are required (such as for hydrogen storage and distribution). Development of skilled human resources required for the emerging fuel cell industry is also important. International codes and standards for fuel cells are considered instrumental to the successful commercialisation of hydrogen fuel cell technologies. Addressing these issues requires productive collaboration between the public and private sectors.

Benefits of fuel cell innovation remain largely in the future

While the economic, environmental and national security benefits of fuel cell innovation are potentially large, they still lie largely in the future. Fuel cell industries have expanded in several countries and employ a growing number of workers, but none of the countries participating in this project are yet able to realise direct economic benefits, with the exception of Canada. To date, most of the benefits of innovation in fuel cell technology have been knowledge benefits. The number of scientific publications related to fuel cells increased more than five-fold between 1990 and 2000, while the number of triadic patent families (for inventions patented in the European Patent Office, Japan Patent Office and US Patent and Trademark Office) increased from seven in 1990 to 158 in 2001. The knowledge codified in these papers and patents, as well as the uncodified knowledge residing in the minds of fuel cell researchers, provide the basis for future innovation and continued development of fuel cell technology. Large-scale commercialisation of hydrogen fuel cells will require continued efforts to further expand and mobilise this knowledge base, with sustained R&D funding and other efforts by both public and private sectors.

Innovation in oil and gas

Fossil energy resources including oil and gas have been and will continue to be the backbone of the energy system in industrialised economies. Together they account for over 60% of fuels supplied to transportation, electric power generation and industrial processes. But innovation in fossil energy resources differs in many ways from innovation in hydrogen fuel cells. Technological innovation in these mature and deeply entrenched energy industries has evolved over a long period of time, more incrementally than by spurts. While the government's role in the innovation of upstream and deep offshore oil and gas technologies is limited, the sheer size of the oil industry implies that public policy can have significant impacts on the entire economy.

Innovation in these fields is driven mainly by economic considerations and, more recently, by environmental concerns. Due to the highly globalised nature of oil markets, technological innovation in upstream oil and gas and in deep offshore oil production is highly susceptible to oil prices. In the case of the US Advanced Turbine System (ATS), innovation was motivated less by economic concerns than by issues of energy security and environmental protection, but economic considerations entered into the government's decision to initiate the ATS programme and provide incentives for innovation.

In the oil and gas sector, innovation is carried out largely by the industry, with more limited roles played by governments. Large firms, in particular, play a dominant role in Norway, where oil companies are the second largest funders of R&D and two oil industry giants (Statoil and Norsk Hydro) account for a large share of the total. In France, the innovation system for deep offshore oil and gas technologies is a triadic organisation consisting of three groups of players: *1)* oil field service companies; *2)* hydrocarbon operating companies; and *3)* higher education and research institutions. In the US ATS programme, the main industrial partners were also large firms, General Electric Power Systems (GEPS) and Siemens Westinghouse Power Corporation (SWPC), although both relied on networks of other smaller firms, and to a lesser extent on public research organisations. Nevertheless, large firms increasingly outsource their R&D and rely on networks of private and public sector organisations for critical elements of innovation.

Public/private partnerships play an important role in bringing about more significant changes in the innovation systems in oil and gas. The advanced turbine system (ATS) was a joint project developed by the US Department of Energy (DOE), and in a cost-shared, public/private partnership that led to successful commercialisation of the technology. Total funding for the ATS project was USD 888 million, of which DOE's share was USD 456 million (51%) and industry's share USD 432 million (49%). The ATS programme produced 55 patents, with GE's share being 23, and SWPC accounting for 28. DOE and universities produced two patents each. French experience indicates that public/private partnerships have helped the innovation of deep offshore oil and gas technologies.

Because innovations in oil and gas have been deployed, there have been economic and environmental benefits. An assessment of the ATS programme found, for example, that against the DOE R&D spending of USD 325 million, economic benefits of USD 5.7 billion could be realised. Environmental benefits were also achieved through reductions in emissions of NOx and CO_2 emissions. Because of the limited sales of the turbines, energy security benefits are small, but significant options benefits and knowledge benefits have been achieved.