

# MAKING CHOICES ABOUT HYDROGEN



TRANSPORT ISSUES FOR DEVELOPING COUNTRIES

EDITED BY LYNN K. MYTELKA AND GRANT BOYLE

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Edited by Lynn K. Mytelka and Grant Boyle

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# Preface

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Recent technological advances in the application of hydrogen fuel cells in the transport sector have drawn considerable attention and increased funding from both public and private sources over the past decade. The International Energy Agency (2005: 35) estimates that about US\$1 billion per year is currently being invested in public hydrogen and fuel-cell research, development, test vehicles, prototype refuelling stations and demonstration projects, as compared to the total annual public budget for energy research, development and demonstration of around US\$8 billion.

While still in the early stages of development and costly in comparison to conventional vehicle propulsion and fuel technologies, hydrogen and fuel cells offer a promising solution to address growing concerns about the transport sector's dependence on oil and its impact on climate change. Although a vigorous debate over the speed with which this will take place is under way, governments have begun to engage in serious discussions on codes and standards for the application of what some see as the leading edge in a new technological revolution.

Like earlier “disruptive” technologies – the replacement of sails by steam power or horses by the internal-combustion engine – hydrogen and fuel-cell technologies will affect a broad range of sectors and have significant social, economic and environmental impacts. How to manage a transition to the application of hydrogen and fuel cells in the transport and energy sectors is not at all clear.

In the importance of their science base, patent intensity and systems embeddedness, hydrogen and fuel cells resemble other new-wave technologies

– information, communications and biotechnology, for example – in the challenges they pose to use and diffusion in developing countries. Most developing countries were singularly unprepared to deal with these earlier waves of new technologies, and the “technological divides” and “knowledge and infrastructure gaps” to which they gave rise are still with us decades later. Yet this need not have been the case. To avoid the problem of exclusion, however, we must pay more attention from the outset to building the local knowledge base and creating the networks that would enable developing countries to set priorities and make policy choices on an informed basis.

In November 2005 UNU took a first step to lay the foundation for access to information flows, networking and local capacity building when it held an international conference in Maastricht on “Hydrogen Fuel Cells and Alternatives in the Transport Sector: Issues for Developing Countries”. The conference was designed to raise awareness of emergent hydrogen and fuel-cell technologies and enhance long-term transport and energy decisionmaking in developing countries. It brought together 35 leading experts from business, government and research organizations in both North and South to review progress in the application of hydrogen and fuel cells in the transport sector and identify key issues for developing countries.

This book is a product of the information exchange and learning processes that began at that meeting and led subsequently to the holding of a side event at the fifteenth session of the UN Commission on Sustainable Development in May 2007. It reflects the continuing debates over hydrogen, fuel cells and their alternatives, and addresses the growing need for a continuous stream of information on new research, innovation strategies and policies.

There are many different types of fuel cells. Alkaline fuel cells (AFCs), for example, were developed in the 1960s to provide on-board electrical power in the US Apollo and space-shuttle programmes. Solid oxide fuel cells (SOFCs) are being commercialized in industry and used for stationary power. It is primarily the proton-exchange-membrane (PEM) fuel cells that were developed for mobile uses.

Fuel cells reverse the long-known process of electrolysis, which uses energy to split water into its components. Instead, fuel cells use a fuel supply to combine hydrogen and oxygen, thus generating an electric current. In the PEM fuel cells that are the current focus of research in applications of this technology in the transport sector, the process is electrochemical and involves an ion-exchange polymer membrane as the electrolyte and electrodes of a fine metal mesh on which a platinum catalyst is deposited. The PEM fuel cell can thus convert hydrogen directly into electricity without combustion or moving parts.

In hydrogen fuel-cell vehicles (HFCVs) the process is virtually pollution free. But the overall utility of HFCVs in reducing greenhouse gases globally depends upon the way the hydrogen itself is produced. If this takes place through renewable processes that are carbon-neutral, such as coupling solar or wind power to electrolyzers that split water molecules into hydrogen and oxygen, the overall impact will be significant.

Technologies such as these, however, are only now being developed and tested, and they face challenges concerning cost and efficiency in the production, distribution, storage and utilization of hydrogen. Currently the most common and cost-effective way to produce hydrogen is through natural gas steam reforming, which reduces the subsequent impact of this new technology on the environment on a well-to-wheel (WtW) basis.

But if a country already produces natural gas, would it not be simpler in the short term to convert from petroleum to natural gas, as buses and taxis in New Delhi have done? Alternatively, would the investment costs in putting a CNG system in place be amortized if hydrogen fuel-cell technology were to become available within the next 15–20 years? And what should be taken into consideration by countries that do not have natural gas? How might they choose between alternatives such as public transport and the automobile or fuels such as ethanol and biodiesel? This volume provides some of the tools needed by decisionmakers to deal with such issues, but the effectiveness of these tools depends critically upon a continuous flow of information.

The large number of hydrogen fuel-cell prototype vehicles, from two-wheelers to cars and buses, already plying the roads in over a dozen countries are accelerating the learning process in the development and use of these technologies. The European Union, for example, is engaged in fuel-cell bus trials in several cities, and foresees that 20 per cent of transport fuel will come from hydrogen by 2020. Japan has a demonstration programme with 60 vehicles and 10 refuelling stations, and has plans to commercialize 5 million fuel-cell vehicles by 2020. The United States is undertaking research and development leading to specific performance targets and a commercialization decision in 2015. Over 100 vehicles and 17 fuelling stations are being tested in the state of California alone. However, the high cost of these demonstration projects has limited the participation of developing countries in this learning process.

A number of lessons have begun to emerge from the experiences shared at the Maastricht conference and the subsequent UNCSD event. There is a need to understand better the technology and its relationship to alternatives. Research, increased knowledge flows and strengthened domestic capacity in science and public policy will be essential in evaluating choices about the development and application of hydrogen fuel cells in the developing world. It has also become evident that information ex-

change, learning and capacity building will have to be started sooner than was the case in new-wave technologies of the recent past. Creating public awareness through demonstration projects that take advantage of key events, such as Canada's Hydrogen Highway planned for the 2010 Winter Olympics and fuel-cell bus demonstrations planned for the World Cup in South Africa, provides some opportunities. Lastly, it is clear that assessing the challenges and the timeframe involved in acquiring, using and adapting hydrogen and fuel cells in the transport and energy sectors, and choosing among alternatives in meeting current goals in the interim, require not only information about the technology itself, but about the multiplicity of pathways, policies and programmes being implemented elsewhere and the varied contexts in which these are achieving their goals. Knowledge flows and networking will thus be critical components in the ability of developing countries to participate fully in the future development of a hydrogen economy and its benefits.

## An outline of the volume

The book is divided into four parts. Part I deals with hydrogen and fuel cells as a disruptive technology. Its focus is on the debate over how soon hydrogen fuel-cell vehicles might become commercially available and whether this will require a considerable amount of new investment in basic research and development, thus pushing the date for commercialization further into the future. The section brings to bear a multiplicity of perspectives on these issues: historical comparisons with the internal-combustion engine and its infrastructure of roads and refuelling stations, and the interplay between enterprise strategies and government policies then and now (Mytelka); the current approach of Japan as it "returns to basics" (Ishitani and Baba) and of the United States, which has set firm targets for moving towards commercialization by the year 2020 (Chalk and Miller); and lastly the role of oil companies in the provision of infrastructure for the hydrogen economy (de Scheemaker).

Part II examines alternative energy sources and their consequences for economic, social and environmental sustainability. It stresses the need to consider the availability of domestic resources in making choices among alternatives, and to take a long-term learning perspective in choosing technological paths for the short term. A wide range of energy and transport options are addressed in this section. On the choice of fuels these include traditional approaches such as the conversion of bus and taxi fleets to CNG (Boyle), the learning about and increased attention to environmental and equity considerations that has taken place in Brazil as a result of its experiences with ethanol, applied in the development

of biodiesel and flex-fuel engines (Teixeira de Sousa et al.), and the need to begin to diversify the energy portfolio in oil-exporting countries (Samuel).

Making choices also involves new considerations on the transport side. A basket of changes, for example, is available to reduce pollution in the Egyptian transport sector. Some of these, moreover, provide the basis for learning about hydrogen without expending the financial resources needed to engage in fuel-cell bus testing now (Abdel Gelil). Iceland, renowned for the extensive use it has made of geothermal energy for heating and electricity generation, now faces choices as it reflects upon the ways to reduce dependence on petroleum for its fishing fleets, cars, buses and planes (Valfells).

Part III looks at the automotive industry, one of the key actors in the transport sector, and presents a set of three contrasting experiences in dealing with an industry undergoing disruptive changes. The chapter on Japan, the world's leading producer of hybrid vehicles, uses data on patenting by Japanese automotive firms to illustrate the diversity of technological trajectories currently being pursued by these companies (Yarime, Kuroki and Shiroyama). Canada, a leading producer of hydrogen fuel cells for the transport sector, has a large automobile production capacity, all of which is owned by multinational corporations. Currently it is not involved in research or production of hybrid vehicles. It faces choices in how to proceed in the use of fuels and types of vehicles in the automotive sector that parallel those in Brazil, China, Mexico, South Africa and other large automobile and auto-parts producers in the developing world (Molot). Malaysia, which has invested heavily in the development of a national automobile company but has not created and enforced policies to stimulate domestic producers to deal with the growing pollution problem at home, has nonetheless developed a hydrogen roadmap that includes major investments in hydrogen and fuel-cell research and development unrelated to its national automobile industry as a potential user of such research (Kari and Rasiah).

Part IV looks at strategies and roadmaps with respect to hydrogen fuel cells and alternatives. Not all countries have developed an explicit strategy for hydrogen and fuel cells, as the United States and Japan have done (see Part I). In the Netherlands, for example, the focus is less on hydrogen *per se* than on the process of exploring energy alternatives that could enable the country to achieve a set of longer-term goals implicit in the notion of a sustainable energy system. The energy transition process, as it is called, is currently under way, and steps in this process and the various learning experiments that are being undertaken in each of its modules are described here (Hoogma).

Among developing countries, a small number have developed policies and strategies with explicit references to the development of hydrogen and fuel cells. China, for example, has three main programme areas in which the focus is on strengthening capacity in fuel-cell development and its application in the bus and automobile industry, which ranks high among contributors to urban pollution (Ming, Lun and Mytelka). The South African strategy, on the other hand, is concerned more with equity issues related to the provision of off-grid energy supply through the use of existing resources and technologies, such as the production of hydrogen through coal gasification or co-generation in a new pebble-bed nuclear reactor and the continued South African role in the supply of platinum, a major input into fuel cells (Mehlomakulu).

Developing a strategy and giving effect to it are not, however, linear processes. In Canada, for example, strategic planning documents have been prepared by various provincial governments, industrial firms or their associations with specific interests in research, development and commercialization of fuel cells for the transport and stationary power industries, and efforts to develop a federal strategy have been made. Prolonged discussion ensued, and changes in government appear to have put this strategy on hold (Fitzgibbons). The Nigerian case presents a similar story. A national policy on science and technology, adopted in 2005, made specific references to the development of the nation's energy resources on a self-sustaining basis and the need to strengthen existing research and development capacities in order to bring this about. A renewable energy master plan that includes hydrogen was under development, but the specific strategy and policies for its implementation had not yet been adopted when a change in government took place (Adegbulugbe, Adenikinju and Momodu).

The chapters in this volume offer many insights into the process of thinking about hydrogen, fuel cells and alternatives and the issues that the emerging hydrogen economy poses for developing countries. These are summarized in a concluding chapter (Mytelka).

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# Acronyms

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AFC	alkaline fuel cell
AFTA	ASEAN Free Trade Area
AFV	alternative-fuel vehicle
AICO	ASEAN Industrial Cooperation Scheme
ANP	National Agency for Petrol and Biofuels (Brazil)
APEC	Asia Pacific Economic Cooperation
ASEAN	Association of Southeast Asian Nations
ASGI-SA	Accelerated and Shared Growth Initiative for South Africa
AT-PZEV	advanced-technology partially zero-emission vehicle
B2	2 per cent biodiesel in diesel oil
B5	5 per cent biodiesel in diesel oil
BB	Bank of Brazil
bb/d	barrels per day
BC	British Columbia
BCF	billion cubic feet
BLCF	Business Linkages Challenge Fund (South Africa)
BNDES	National Bank for Social and Economic Development (Brazil)
bpd	barrels per day
CAIP	Cairo Air Improvement Program
CARB	California Air Resources Board
CAS	Chinese Academy of Sciences
CBU	completely built-up
CDM	clean development mechanism
CEO	chief executive officer
CETESB	Companhia de Tecnologia de Saneamento Ambiental (Environmental and Sanitation Technology Company), Brazil

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CFCP	California Fuel Cell Partnership
CH <sub>4</sub>	methane
CHP	combined heat and power
CKD	completely knocked-down
CNG	compressed natural gas
CO	carbon monoxide
CO <sub>2</sub>	carbon dioxide
COG	coke-oven gas
COP3	Third Conference of Parties (of the UNFCCC)
CSIR	Centre for Scientific and Industrial Research (South Africa)
CTA	Cairo Transient Authority
CTFCA	Canadian Transportation Fuel Cell Alliance
CUTE	Clean Urban Transport for Europe
DCX	DaimlerChrysler
DFID	Department for International Development (UK)
DICP	Dalian Institute of Chemical Physics
DME	di-methyl ether
DMFC	direct-methanol fuel cell
DND	Department of National Defence (Canada)
DOE	Department of Energy (USA)
DOE	Department of Environment (Malaysia)
DOT	Department of Transportation (USA)
DST	Department of Science and Technology (South Africa)
ECN	Energy Commission of Nigeria
ECTOS	Ecological City Transport System
EEAA	Egyptian Environmental Affairs Agency
EIA	environmental impact assessment
EJ	exajoule
ENAA	Engineering Advancement Association of Japan
ENR	Egyptian National Railways
EPA	Environmental Protection Agency (USA)
EPCL	Eleme Petrochemicals Company
EPSD	Electric Power Safety Division (Japan)
EPU	Economic Planning Unit (Malaysia)
EQA	Environment Quality Act (Malaysia)
EV	electric vehicle
EWG	APEC Energy Working Group
FC	fuel cell
FC <sup>3</sup>	Polymer Electrolyte Fuel Cell Cutting-Edge Research Center (Japan)
FCB	fuel-cell bus
FCCJ	Fuel Cell Conference of Japan
FCT	Federal Capital Territory (Nigeria)
FCV	fuel-cell vehicle
FDMA	Fire and Disaster Management Agency (Japan)
F-T	fischer-tropsch process
G21	Global 21st Century project

GCBC	Greater Cairo Bus Company
GDP	gross domestic product
GE	General Electric
GEF	Global Environment Facility
gge	per gallon gasoline equivalent
GH	gaseous hydrogen
GHG	greenhouse gas
GM	General Motors Corporation
GTL	gas-to-liquids
GW	gigawatt
GWh	gigawatts per hour
ha	hectare
HB	Housing Bureau (Japan)
HC	hydrocarbon
HEV	hybrid electric vehicle
H&FC	hydrogen and fuel cells
HFC	hydrogen fuel cell
HFCV	hydrogen fuel-cell vehicle
HICOM	Heavy Industries Corporation of Malaysia
hp	horsepower
HTR	high-temperature reactor
H2V	Hydrogen Village (Canada)
HYSON	Hydrocarbon Services of Nigeria
IC	internal-combustion
ICC	International Code Council
ICE	internal-combustion engine
ICEV	internal-combustion-engine vehicle
ICHET	UNIDO International Centre for Hydrogen Energy Technologies
ICT	information and communications technology
IDRC	International Development Research Centre (Canada)
IE	Intelligent Energy
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IERD	Industry Energy Research and Development (Canada)
IMF	International Monetary Fund
INE	Icelandic New Energy
INSPAK	Public Transport System in Klang Valley
INT	Instituto Nacional de Tecnologia (Brazil)
IP	intellectual property
IPHE	International Partnership for the Hydrogen Economy
IRPA	intensive research priority area
ISD	Industrial Safety Division (Japan)
ISO	International Organization for Standardization
JAMA	Japan Automotive Manufacturers' Association
JARI	Japan Automotive Research Institute
JEMA	Japan Electrical Manufacturers' Association

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JEVA	Japan Electric Vehicle Association
JGA	Japan Gas Association
JHFC	Japan Hydrogen and Fuel Cell project
JIA	Japan Gas Appliances Inspection Association
JICA	Japanese International Cooperation Agency
KLSE	Kuala Lumpur Stock Exchange
KRPC	Kaduna Refining and Petrochemicals Company
ktoe	kilowatt tonnes of oil equivalent
KT/Y	kilo tonne per year
kW	kilowatt
kWh	kilowatt hour
LCA	life-cycle assessment
LE	Egyptian pound
LEV	low-emission vehicle
LH	liquid hydrogen
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LRT	light-rail transit
mbpd	million barrels per stream day
MC	Mitsubishi Corporation
MEA	membrane electrode assembly
MEC	Malaysian Energy Centre
METI	Ministry of Economy, Trade and Industry (Japan)
MLIT	Ministry of Land, Infrastructure, Transport and Tourism (Japan)
MMBTU	million British thermal units
MMC	Mitsubishi Motor Corporation
MNE	multinational enterprise
MOE	Ministry of Environment (Japan)
MoST	Ministry of Science and Technology (China)
MOSTE	Ministry of Science, Technology and Environment (Malaysia)
MOSTI	Ministry of Science, Technology and Innovation (Malaysia)
MOU	memorandum of understanding
MPa	megapascal
mpg	miles per gallon
mph	miles per hour
Mt	million tonnes
MTBE	methyl tert-butyl ether
Mtoe	million tonnes of oil equivalent
MT/Y	metric tonnes per year
MW	megawatt
MWe	megawatts of electrical power
NAFTA	North American Free Trade Agreement
NCE	Network of Centres of Excellence (Canada)
NECAR	New Electric Car
NEDO	New Energy and Industrial Technology Development Organization (Japan)

NEEDS	National Economic Empowerment and Development Strategies (Nigeria)
NGC	Nigerian Gas Company
NGO	non-governmental organization
NGP 2010	Nissan Green Program 2010
NGV	natural gas vehicle
NISA	Nuclear and Industrial Safety Agency (Japan)
NNAA	new North American assemblers
NNPC	Nigeria National Petroleum Corporation
N <sub>2</sub> O	nitrous oxide
NO	nitrogen oxide
NO <sub>2</sub>	nitrogen dioxide
NO <sub>x</sub>	nitrogen oxides
NRC	National Research Council (Canada)
NRC	National Research Council (USA)
NRCan	Natural Resources Canada
NRC-IFCI	NRC Institute for Fuel Cell Innovation (Canada)
NRC-IRAP	NRC Industrial Research Assistance Program (Canada)
NREL	National Renewable Energy Laboratory (USA)
NSERC	Natural Sciences and Engineering Research Council (Canada)
OECD	Organisation for Economic Co-operation and Development
OEERE	Office of Energy Efficiency and Renewable Energy (USA)
OEM	original equipment manufacturer
OEP	Organization of Energy Planning (Egypt)
OFE	Office of Fossil Energy (USA)
ONE	Office of Nuclear Energy, Science and Technology (USA)
OPEC	Organization of Petroleum Exporting Countries
OSC	Office of Science (USA)
PAFC	phosphoric acid fuel cell
PAJ	Petroleum Association of Japan
PBMR	pebble-bed modular reactor
PEC	Petroleum Energy Center (Japan)
PEM	proton-exchange membrane/polymer-electrolyte membrane
PEMFC	proton-exchange-membrane fuel cell
PFC	perfluorocarbon
PGM	platinum-group metal
PHRC	Port Harcourt Refining Company
pj	petajoule
PM	particulate matter
PPA	power purchase agreement
PPMC	Pipelines and Product Marketing Company
PRC	People's Republic of China
PSA	pressure swing adsorption
psi	pounds per square inch
Pt	platinum
PTL	Powertech Labs
PV	photovoltaic

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PZEV	partially zero-emission vehicle
R&D	research and development
RB	Road Bureau (Japan)
RD&D	research, development and demonstration
RD&D	research, development and dissemination
RE	renewable energy
RED	NNPC Renewable Energy Division
RET	renewable energy technology
RH	relative humidity
RPS	renewable portfolio standard
RTB	Road Transport Bureau (Japan)
RTD	Road Transport Department (Malaysia)
SAIC	Shanghai Automotive Industry Corporation
SAIMC	South African Institute for Advanced Materials Chemistry
SAP	structural adjustment programme
SDTC	Sustainable Development Technology Canada
SET-Plan	EU Strategic Energy Technology Plan
SIRIM	Standards and Industrial Research Institute of Malaysia
SMEs	small and medium-sized enterprises
SNG	synthetic natural gas
SO <sub>2</sub>	sulphur dioxide
SOFC	solid oxide fuel cell
SO <sub>x</sub>	sulphur oxide
SR&ED	Scientific Research and Experimental Development programme (Canada)
S&T	science and technology
SULEV	super-ultra-low-emission vehicle
SUV	sport utility vehicle
SWNT	single-walled carbon nanotube
TCF	trillion cubic feet
TEAM	Technology Early Action Measures (Canada)
TEL	tetraethyl lead
TEP	tonne equivalent of petroleum
TPC	Technology Partnerships Canada
TRIMS	Agreement on Trade Related Investment Measures
TRIPS	Agreement on Trade Related Aspects of Intellectual Property
TtW	tank-to-wheel
TWh	trillion watt hours/terawatt hour
TWh/a	TWh per annum
UKM	National University of Malaysia
UNCSD	UN Commission on Sustainable Development
UNDP	UN Development Programme
UNFCCC	UN Framework Convention on Climate Change
UNIDO	UN Industrial Development Organization
UNU	United Nations University
UNU-ESD	UNU Environmental and Sustainable Development Programme
UNU-GTP	UNU Geothermal Training Programme

UNU-INTECH	UNU Institute for New Technologies
UTM	University of Technology of Malaysia
UTM	University of Toronto Mississauga
UTS	urban transit system
VCR	videocassette recorder
WBCSD	World Business Council for Sustainable Development
WG	working group
WHO	World Health Organization
WTO	World Trade Organization
WtT	well-to-tank
WtW	well-to-wheel
ZEV	zero-emission vehicle

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Part I

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Hydrogen and fuel cells:  
An ongoing debate

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# Introduction

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Since the mid-1990s the emergence of a hydrogen economy and the speed with which this will arrive have been vigorously debated. The debate has mainly been carried on among policymakers and oil and gas, automobile, fuel-cell and renewable energy firms in the countries of the North, where policies and the technological competences and competitive practices of firms have played a central role in shaping both the debate and the direction of technological change during this period. Part I looks at this debate as it relates to the development and commercialization of hydrogen and fuel cells in the transport sector.

For developing countries the current debate highlights the uncertainties involved in making choices about hydrogen and fuel cells in planning the development of their transport sector. As a disruptive technology, dominant designs for the production, storage and distribution of hydrogen have not yet been established. Nor have performance characteristics been achieved that would make hydrogen proton-exchange-membrane (PEM) fuel cells competitive with the internal combustion engine. Yet costs are coming down and the efficiency and durability of hydrogen fuel cells (HFCs) are improving. How to deal with competing arguments that push the hydrogen economy into the longer term (2050) and those that place its advent in a shorter-term perspective (2020) is one key issue for developing countries today as they explore their options for the design of national energy, environment and transport policies.

The chapter by Mytelka sets out a framework for understanding this debate and applies it to two historical cases – oil and the internal-combustion

engine – where many of the issues raised in current debates over fuels and fuel cells first emerged. One of these was the need for further basic research to make the early gasoline-based internal-combustion engine competitive with the alternatives of its day. The extent to which further basic research will be needed before commercialization of hydrogen fuel-cell vehicles is feasible parallels this earlier concern. A second is the speed with which progress is made in bringing down the cost of hydrogen production, storage and transportation and of the hydrogen fuel cells themselves. The Ishitani and Baba and the Chalk and Miller chapters engage in a discussion of these issues; they also highlight the importance of broad-based public participation in such debates and the creation of public-private partnerships in developing the codes and standards that the commercialization of hydrogen fuel-cell vehicles will require at both national and international levels. At present, only a very few developing countries are participating in this process.

A third issue of concern to developing countries, where transport and refuelling infrastructure of all sorts still needs to be built, is the chicken-and-egg problem that arises with respect to hydrogen infrastructure. This results from the need to coordinate a large number of different actors, both public and private, and the uncertainties surrounding the choice of hydrogen delivery system: at the pump or through decentralized modes such as hydrogen to the home – an innovative design still in its infancy. From a business perspective, the chapter by de Scheemaker takes the position that in the shorter term using existing infrastructure will be more cost-effective. It also argues for a demand-driven approach in which public policy helps to create the market for hydrogen, to which the private sector would respond by building the necessary infrastructure. Although the chapter notes that the hydrogen economy is still some 20 years away, it points to the importance for developing countries of learning from the experiences of developed countries in building hydrogen infrastructure and the need to begin a process of designing their own hydrogen roadmaps.

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# Hydrogen fuel cells and alternatives in the transport sector: A framework for analysis

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*Lynn K. Mytelka*

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## Introduction

In the mid-1990s, fuel cells came to be regarded as a promising technology in the transport sector. Barely 10 years earlier they were hardly on the technological horizon and the idea of a fuel-cell vehicle was only a glimmer in the eyes of a few visionaries. By the end of that decade fuel-cell vehicles were being touted as the wave of the near future. Yet today that horizon appears to have receded. How can we explain such radical shifts in perceptions with regard to this emerging technology?

To argue that we have simply returned to reality after a period of “hype” neither enables us to assess the realism of the former nor serves to explain the pessimism of the latter. This chapter thus begins by presenting a framework to help analyse the process of technological change and plan for it better. The framework sets out a number of broad factors that have tended to shape the speed and direction of technological change.

Of critical concern in this chapter and the book as a whole are the issues that these changes raise for developing countries, particularly in “new-wave technologies” such as information and telecommunications, biotechnology and the technologies that underlie the emerging hydrogen economy. These are identified throughout this chapter.

The chapter then establishes a baseline for the analysis of non-linearity that has marked the development of hydrogen fuel-cell vehicles (HFCVs) since the 1990s. It does so by using the framework to explore the

emergence of a dominant design for the internal-combustion engine (ICE) and the subsequent evolution of automobile technology based on this motive force. Going beyond technological constraints, this chapter pays particular attention to the institutional and economic considerations that led to the dominance of gasoline over electric-powered vehicles. The co-evolution of technology in the oil industry is also discussed, as this is raised today in connection with the speed at which hydrogen can be provided to support HFCVs.

The chapter then applies the approach to analyse the emergence and development of proton-exchange-membrane (PEM) fuel cells across two periods – the “turning-point years” from 1994 to 2001 when a steep rise in interest and activity took place, and a period of questioning and renewed debate in the “questioning years” that began in 2002. It identifies a number of factors that affected the speed with which HFCVs were moving towards commercialization in each period. In this context, it includes a brief review of alternatives to hydrogen as a fuel in HFCVs and of alternatives, such as hybrid vehicles, to the fuel-cell vehicles themselves. This lays the basis for an introductory discussion on the theme of choice-sets and priority setting that continues throughout this book.

## A framework for the analysis of technological change

Models of broad-based technological change frequently referred to in the literature as technological revolutions (Utterback, 1994; Freeman and Perez, 1988; Perez, 2002) traditionally distinguish three phases in the emergence and development of a technology. The first is the period in which the new technology emerges, product innovation is intense and product variety widens. This is followed by a transitional phase during which competition in the marketplace or performance standards set by law lead to the establishment of a dominant product design (Utterback and Abernathy, 1975) and open opportunities for standardization and mass production.<sup>1</sup> The third phase is that of the mature technology. Innovation continues to take place, but incrementally along the established technological trajectory.

With hindsight, the history of the internal-combustion engine appears to have followed such a linear path, as did other mechanically based technologies of the past. But such an approach misses the many “inducement mechanisms and focusing devices” (Rosenberg, 1976) that shaped the branching points in these technological trajectories over time (Dosi, 1988). Most of this earlier literature also failed to take into account the context within which these selection mechanisms operated, and this has had particular ramifications for technological choice and the effectiveness

of technology transfer to developing countries (Stewart, 1977: 22–29; Mytelka, 1985, 2004).

New-wave technologies such as information and communications technologies (ICTs), biotechnology, nanotechnology and hydrogen-based technologies, moreover, have three defining features that differentiate them from these earlier industrial technologies: their science base, patent intensity and systems embeddedness. These differences suggest that the forces and factors shaping the pattern of technological change are also likely to differ, as will their impact on developing countries. In both deepening our understanding of innovation in earlier mechanical technology and providing a predictive tool to analyse the process of technological change in new-wave technologies, a more systems-oriented approach is thus needed.

This chapter applies an innovation systems approach to analyse the establishment of the internal-combustion engine in the automotive industry of the early twentieth century, and the emergence of hydrogen fuel cells as a possible successor as that century drew to a close. Its focus is on the firms and other actors which, together with the institutions and policies that influence their innovative behaviour and performance, bring new products, new processes and new forms of organization into economic use. At the core of an innovation system are the flows of knowledge and information that link economic actors and provide both a stimulus to and the support for innovation. Underlying the “system of innovation” approach is an understanding of innovation as an interactive process and a reconceptualization of firms and other actors as learning organizations embedded within a broader institutional context (Nelson and Winter, 1982; Freeman, 1988; Lundvall, 1988). Institutions in this sense are not formal structures or organizations but “sets of common habits, routines, established practices, rules or laws that regulate the relations and interactions between individuals and groups” (Edquist, 1997: 7) and thus “prescribe behavioural roles, constrain activity and shape expectations” (Storper, 1998: 24). Habits and practices such as these are learned behaviour patterns, marked by the historical specificities of a particular system and moment in time (Mytelka, 2000). Over time, therefore, their relevance may diminish as conditions change. Policies, whether tacit or explicit, can speed up or retard this process by setting the parameters within which actors in the system make decisions about innovation.

For developing countries, the characteristics of new-wave technologies themselves will shape opportunities and constrain choices over the short and longer term. Anchored in the sciences, the knowledge base of new-wave technologies has developed less as the result of incremental change along a single technological trajectory than through a combination of several distinct trajectories with significantly different scientific roots. These

diverse roots, however, increasingly share a common platform – that of working at the nano-level of photons and genes.<sup>2</sup> As a result, the research laboratory has become central in the discovery and development of new products and processes based on new-wave technologies.<sup>3</sup>

Earlier models of technological change based on experience with industrial technologies have traditionally distinguished between innovation in products and in production technologies, and generally regarded these as sequential processes (Utterback and Abernathy, 1975). This allowed for a more incremental process of catching up. New-wave technologies, however, tend to fuse product and process innovation at the experimental stage – that is, in the laboratory. The importance of systematic research, and the centrality of the research laboratory that this implies, puts developing countries at a disadvantage.

The products of new-wave technologies are also combinatorial. On the input side, the ability to develop such products and establish a “dominant design” in industries growing out of new-wave technologies has depended upon innovations from across a wide range of scientific and industrial domains. On the output side, these are rarely stand-alone products. Systems integration is so common a feature of new-wave technologies that they have often been described as “generic” technologies. These characteristics favour research systems with a wide range of knowledge bases. Yet few developing countries have such capabilities at present.

A number of consequences for the pattern of competition flow from the high costs and risks inherent in science-based innovation, the combinatorial nature of new-wave technologies and the systems-integrated nature of their products. These add to the difficulties faced by developing countries in catching up.<sup>4</sup>

Size and scale, for example, remain critical in the manufacture of products based on new-wave technologies, and these are radically changing the nature of competition in industries in which these technologies are applied. Historically, incremental changes that enhance the manufacturability of products and economies of scale in production have been critical in reducing costs and speeding technological diffusion, and they remain important despite the greater role that science plays in new-wave technologies. It would be misleading, therefore, to assume that technological knowledge “acquired and accumulated in crude empirical ways, with no reliance upon science” would not continue to play a role (Rosenberg, 1982: 143), as it did in the refinement of products and manufacturing processes in earlier waves of technological change.<sup>5</sup> Once again, however, new-wave technologies exhibit a variation on this theme in several ways.

The combinatorial nature of products based on new-wave technologies and their integration into the products and processes of other technological systems open the way for larger firms to play a more prominent role than in the past in shaping the technological trajectory and the speed with which new-wave technologies are incorporated into the production process. The cascade of products flowing from the application of micro-processors and lasers to audio-visual equipment, for example, has been shaped by only a handful of large firms and their partners (Delapierre and Mytelka, 2003). The application of biotechnology in the pharmaceutical sector has followed this pattern, and one would expect something similar to emerge in the development of fuel-cell technology.

Strategies of knowledge generation and appropriation that privilege larger firms are also playing a more significant role in new-wave technologies than in earlier mechanical technologies. In this, they resemble those few science-based industries of the past – chemicals, petrochemicals and later pharmaceuticals<sup>6</sup> – whose relatively high research and development (R&D) costs were partly amortized through patenting. Though patenting might, under other circumstances, strengthen the role of small innovative firms, new-wave technologies do not exhibit the traditional Schumpeter (1939) pattern of industrial dynamics in which innovation gives rise to a high rate of new firm entry in a variety of new industrial segments and the gradual replacement of incumbents by newcomers. Consolidation is more often the case.

Size has also been an important element in the appropriation of knowledge that enabled established firms to remain dominant. In the application of biotechnology to pharmaceuticals, for example, ever-larger pharmaceutical firms have been able to appropriate new knowledge through in-house R&D, a high level of patenting activity, mergers and acquisitions and partnerships of various sorts, including the development of knowledge-based networked oligopolies (Mytelka, 2001). For developing countries, the success of efforts to develop uniform intellectual property rules at the global level<sup>7</sup> has broadened the scope of patents, inevitably narrowing the path around an invention and limiting opportunities for innovation locally. Extending the duration of patent lives under such agreements adds to this problem by significantly reducing the commercial incentives to engage in reverse engineering – the classic form of knowledge spillover that contributed so significantly to rapid development in Asia in the last decades of the twentieth century. This, too, has disadvantaged developing countries in their ability to catch up and keep up with a moving frontier.

Moving an innovation from laboratory to the market, moreover, increasingly requires partners, and a pattern of precocious partnering for

R&D as well as standard setting has developed in industries based on ICTs (Mytelka, 2001) and biotechnology (Mytelka, 2003). This, in turn, has given rise to changes in the nature of competition in the emergent and transitional phases of these technologies. In contrast to the arm's-length firm-to-firm competition characteristic of earlier waves of technological change, in industries based on new-wave technologies competition takes place among networks of firms bound to each other through a variety of alliances. Few firms from the developing world are partners in these knowledge networks (Kim and Nelson, 2000; Verspagen, 2005).

The emergence of knowledge-based networks that extend across borders and industries has stimulated a pattern of oligopolistic market competition on a global scale. Unlike traditional oligopolies based on the statics of cross-licensing and market sharing, however, knowledge-based networked oligopolies involve collaboration in the creation of new knowledge and control over its evolution. They are dynamic, seeking to shape future technological trajectories as opposed to merely rigidifying the status quo. Through mutual forbearance and attention to the market strategies of rivals, oligopolistic competition among these knowledge-based networks may accelerate the process of technological diffusion at the same time as it structures the form and direction that technological change takes. This was evident in a variety of segments within the ICT sector, and how such competitive processes unfold will undoubtedly affect the speed with which fuel-cell technologies are applied in the automotive sector.

The third characteristic that new-wave technologies share is their systems embeddedness. This has a bearing on both the speed and the direction of technological change. The combinatorial nature of their products and their embeddedness in complementary technological systems, for example, require a high level of systems integration and large-scale investments in new infrastructure as part of the process of establishing a dominant design. Most developing countries, as the experience with telecommunications technologies from the telephone to the internet has shown, do not have access to the capital needed to build such infrastructure and thus face relatively long-term lags in access to the benefits of new-wave technologies.

The further development and diffusion of these technologies are shaped by two other sets of constraints emanating from the economic and social systems in which they are also embedded. Because of the uncertainties and systems embeddedness in new-wave technologies, successful innovation processes are highly interactive. This opens channels for critical flows of knowledge and information, and assists in coordinating the development of new infrastructure where it is needed. When such coordination involves changes in the habits and practices of consumers and

producers, facilitating interaction may require the creation of systems-level intermediary organizations (van Lente et al., 2003). Traditionally, public policies have thus played a role in stimulating the emergence of such intermediaries in addition to shaping the parameters within which decisions about innovation are made by actors in the system.<sup>8</sup> This can be expected to alter the pace of change significantly, especially in new-wave technologies where research and infrastructure costs are high and there is a need for extensive dialogue and coordination.

New-wave technologies are by definition disruptive. In the genesis and emergence of such technologies there is always some degree of discontinuity in infrastructure and institutions, and thus a need to learn new ways of doing things and unlearn habits and practices of the past. The more embedded a technology is in other systems, the higher the risks to enterprises in their development and diffusion and the greater the resistance to change. Market forces alone, therefore, often fail to stimulate and support an innovation process when coordination requirements are high. The relative weight between the different parametric considerations that affect the speed and form of technological change can, however, be shifted through a broad range of government policy initiatives, in the absence of which transition periods may be longer, more difficult and more costly.

The basic contours of the approach taken here in analysing the time horizon available to developing countries before the next wave of technology bursts upon them are graphically represented in figure 1.1, and

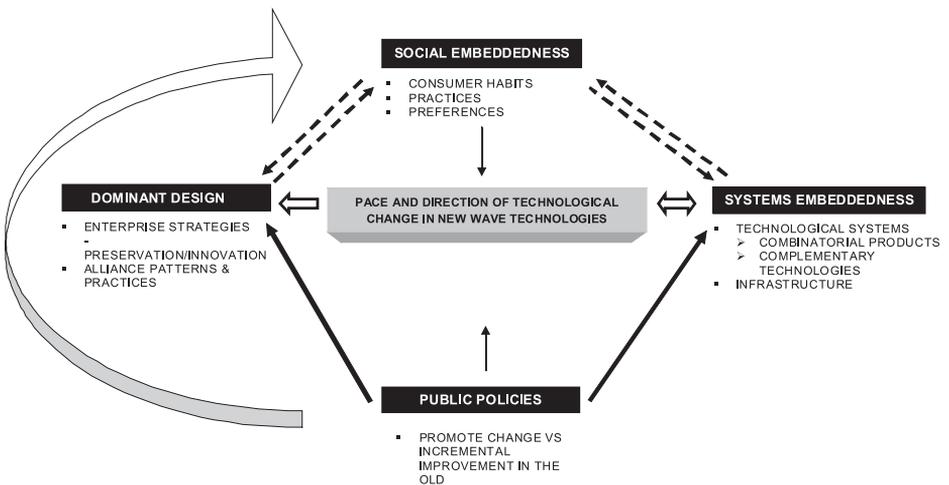


Figure 1.1 New technologies and developing countries

can be summed up in the following terms: the pace and direction of technological change are largely a function of the speed with which a dominant design emerges, costs are reduced and systemic constraints are removed.

Each of these broader variables can be further decomposed. For example, the speed with which a dominant design emerges in new-wave technologies will probably depend upon the availability of finance for research and on technological integration. Both the speed at which a dominant design emerges and its movement down the cost curve in industries based on these technologies will also depend on the formation of alliances through which standards can be set and the closer coordination needed for technological integration can take place. This will permit the development of economies of scale and scope which are prerequisites to cost reduction. Policy can play a major role in removing the constraints flowing from systemic embeddedness by altering the trade-offs between the relative costs and risks of “preservation versus innovation” for the enterprise and the consumer.<sup>9</sup>

In the following two sections this framework is applied to analyse the pace and direction of technological change in the adoption of the internal-combustion engine and HFCVs.

## Shaping technological change: The internal-combustion engine

The emergence of the modern automobile can be dated to 1885, when the first vehicle propulsion by an internal-combustion engine was developed in Germany simultaneously by Karl Benz and Gottlieb Daimler, and patented by the latter (Graedel and Allenby, 1998). The hand-crafted automobiles of this period, however, were luxury products – “the playthings of the wealthy few” (Utterback, 1994: 127). By 1906, more than two decades after the first automobiles had appeared in Europe, the total number of such vehicles being produced across the whole of Western Europe each year was only 50,000 (Hoffman and Kaplinsky, 1988: 74). By that time, however, the gasoline-fuelled internal-combustion engine had emerged as the dominant design in motor cars.

There was nothing inexorable about the internal-combustion engine’s victory over steam power and electricity in the motor vehicles of the twentieth century. Why it triumphed was certainly not due initially to its superior technology, if superiority is measured by power, efficiency or reliability. Nor was the infrastructure in place to smooth the introduction of faster-moving vehicles or long-distance driving. When compared with electric vehicles there were many trade-offs to consider. For example,

although the range of electric vehicles before batteries needed recharging was far lower than the range between refuelling stops, the fuel in internal-combustion engines was itself a problem and led to frequent stalling. Compared to electric trucks, ICE-powered vehicles were also more expensive and their use required more extensive organizational changes as well as significant modifications to existing habits and practices, notably in the delivery service sector. Normally this would have implied a considerable resistance to change. How then do we explain the speed with which the gasoline-powered ICE became the dominant design in motor vehicles? Why did a decades-long difference emerge in its establishment as the leading technology in the passenger-car market and in the market for commercial vehicles?

A chronology of key technological changes that gradually increased the flexibility, power and dependability of the ICE is only a starting point, since “Technical superiority resided not simply in the physical properties of the individual technologies but in the contexts and systems in which motor vehicles were embedded” (Mom and Kirsch, 2001: 491). How that environment is perceived and defined, how the range of choices is delimited and how parameters are set within which these choices are made are critical factors in pushing and pulling new technologies along or applying the brakes.

The transitional period, for example, was marked more by changes in production processes and organizational structures than by substantive technical changes in the internal-combustion engine, though a number of innovations were introduced to increase engine power and make driving a motor vehicle easier.<sup>10</sup> The major production innovation, for which the era is better known, was the adoption of automatic materials transfer in the manufacture of the Ford Model T. This speeded up the flow of parts and their assembly, making mass production a reality (Best, 1990). By 1914 the Ford assembly line alone was capable of producing 300,000 vehicles per year and the price of cars dropped dramatically (Hoffman and Kaplinsky, 1988: 74). Techniques of mass production were subsequently adopted elsewhere. Daimler-Benz, for example, was in the forefront among European producers. The transition period drew to a close when the Model A was introduced in 1928, followed shortly by the V.8 engine series. Organizationally, the corporate model came to dominate the industry, beginning with the incorporation of General Motors (GM) in 1908 and a few months later its acquisition of Buick.<sup>11</sup> Other companies soon followed suit.

Despite their many technological shortcomings, between 1908 and 1927 some 15 million Model T Fords were sold. Yet this was also the period in which gasoline-powered commercial vehicles were vigorously challenged by electric trucks (Mom and Kirsch, 2001). The latter had

displaced horse-drawn wagons for short-haul transport from railheads. Like the horse-drawn wagon, the electric delivery van was inserted into a broader context, that of the “service economy” in which local department stores, breweries and other manufacturers participated as a means to win customer loyalty in urban areas. In this market, internal-combustion engines were too costly to operate, since the principal advantage of such vehicles was their greater range between refuelling stops. Operating over a larger range and with less downtime while customers opened packages, inspected goods, tried on merchandise or tapped kegs were critical in amortizing the higher initial price of the gasoline-fuelled internal-combustion engines which powered these vehicles. At the time, moreover, neither the power nor the reliability of these trucks was sufficient to challenge the trains that dominated the long-haul market. It was not until these trucks could provide universal service across both markets that they posed a real challenge to the electric vehicle. Even then the choice was not based solely on technological strengths or even the habits and practices of the service economy, which would later be forced to change, but on errors in competitive strategy that weakened the electric vehicle (EV) as a vehicle of choice. The ability of EVs to compete in medium-haul markets, for example, was seriously weakened by the strategy of electric generating stations, notably in the United States, to monopolize the supply of electricity by integrating downstream to garages where electric cars and trucks could recharge their batteries. The alternative was to change batteries, a practice adopted at various times in Europe but one that never took hold in North America. Many of these factors reappear in the context of challenges to and pressures for the use of hydrogen fuel cells in the transport sector, as will be seen in the next section.

The continued development and widespread use of the automobile powered by an internal-combustion engine in the post-transition period were for many years constrained by a number of other systems within which it was embedded. One of these was the system of refining fuels, including the development of catalytic-cracking processes (Freeman, 1982: 62): improvements in the anti-knock quality of the fuel, expressed as its octane number, and higher extraction of gasoline from the same quantity of petroleum through the use of heat, pressure and catalysts to rearrange the molecules of economically less important distilled fractions.

Mechanical innovations designed to solve the problems of carburation, valving and ignition could only go so far in making engines more efficient. This was because further improvements in engine design could not succeed in generating power and reliability in the absence of better-quality fuels. Why did the oil industry not move more quickly to improve fuel

quality? Here again, one of the critical issues was how oil companies perceived their role and framed the problem. Petroleum-refining technology was an adaptation of earlier coal-oil processes and as such was based on thermal cracking. As the car market developed, the oil industry framed the problem as one of a potential fuel shortage. Its objective thus became the extraction of more gasoline from existing refineries. This was done by developing a continuous process of thermal cracking. The anti-knocking properties of tetraethyl lead were known<sup>12</sup> and it was being added to gasoline in the 1920s. But this did little to raise the compression ratio of automobile engines or increase their efficiency. It was not until demand for higher-quality fuels from the emerging aviation industry rose that research began in earnest to build the chemical knowledge needed to develop a continuous process of catalytic cracking and raise the octane levels of refined oil. The research was undertaken in the mid-1930s by a consortium put together by Standard Oil of New Jersey. The consortium spent US\$15 million over three years to produce more refined oil which made possible higher compression ratios that increased engine power and eliminated stalling.

The second constraint on the continued growth of the automobile industry was the infrastructure upon which it depended, notably a distribution network for gasoline and a system of paved roads and highways. Standard Oil, which had been founded in the United States in 1865, was innovative in locating its refineries near railroad lines and planning oil shipments so that railroad companies could make up daily oil trains. Investments in pipelines to link oil fields with refineries and railroads were undertaken later. Some usable infrastructure was thus in place when the sale of automobiles began in earnest. Roads were another matter, since the competition with railroads for long-distance travel had favoured the latter during the nineteenth century. Public financing of roads and highways was an important factor in the widespread development of a road network after the First World War.<sup>13</sup>

In the “mature” phase, technological progress was slow and took place along an incremental technological trajectory marked by trade-offs between power, efficiency and fuel economy. These are often attributed to consumer preferences. In the decades before the oil crisis in 1973 an overall reduction in mechanical novelty and variety resulted, although options proliferated (Abernathy, 1978). Changes that did occur in production processes, moreover, led to such dedicated systems that opportunities for further innovation were significantly reduced.<sup>14</sup> As the problem of emissions was slowly recognized, the solution was reconceptualized within this nexus and strategies of preservation rather than innovation resulted. “It is not that automotive technologies haven’t improved; it’s that

the improvements have been geared towards delivering power, not efficiency” (Fischetti, 2002: 42). The choice of an incremental path that favoured preservation over innovation can be illustrated by the evolution of carburettor and fuel-injection systems and the adoption of the catalytic converter.

Efficient operation of gasoline spark-ignition engines, for example, depends on the air-fuel mixture. Ensuring that the mixture is delivered to the combustion chamber well atomized and at exactly the right ratio of air to fuel can be carried out by a carburettor or a fuel-injection system.<sup>15</sup> The camshaft, a century-old mechanism that opens and closes the engine valves which let the fuel-air mixture into the combustion chambers and release exhaust gases, is still the dominant design. “A spinning shaft, it moves levers that open and close valves approximately 100 times per second in a fixed pattern” (ibid.: 46). This wastes fuel. Electronic controls have been introduced that allow some valve control, for example to open valves only partway when little power is needed, but a real breakthrough would be to substitute electromechanical activators for the camshaft. These would provide software-driven control for each valve. Unfortunately current technology is not yet able to do this without excessive wear, engine noise and vibration (ibid.). Gasoline direct injection and digital microprocessors to control fuel and injection systems and spark advance are only the latest improvements designed to preserve the mechanical base of this ageing system.

The problem of emissions was recognized as early as the 1940s. By the mid-1960s motor vehicles were creating 86 million tonnes of pollutants per year, most of which was carbon monoxide. Unburned fuel, nitrogen oxides, sulphur oxides, particles and lead compounds made up the rest. As in other cases, the habits and practices of the actors and the way they framed the solution have meant a lengthy race to the bottom, as automobile manufacturers adopted the catalytic converter rather than undertaking more radical change. In 1965 the state of California adopted the first legislation to control exhaust products. The US federal government adopted identical laws two years later.

The initial reduction in carbon monoxide and unburned fuel emissions was undertaken by modifying carburation, using a leaner mixture and modifying ignition timing. This reduced compression ratios, but these would increase again with some refinement in combustion-chamber designs to allow faster burning of the fuel (Somerscales and Zagotta, 1989). Sulphur oxides and lead compounds were to be eliminated from the fuel. With the reduction in federal hydrocarbon and carbon monoxide emissions standards in 1975, the catalytic converter – an end-of-pipe solution that reduced the need for further innovation – rapidly became the dominant design in dealing with the emissions problem over the next

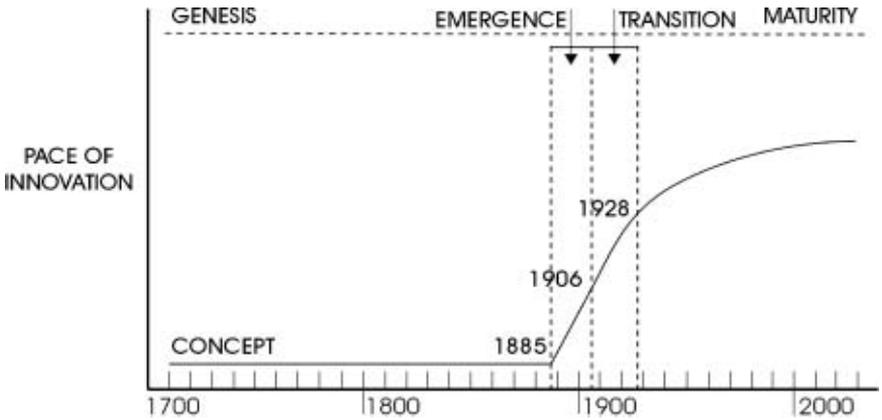


Figure 1.2 Development of the internal-combustion engine

few decades (ibid.; Newcomb and Spurr, 1989). Figure 1.2 illustrates the incremental development path of the internal-combustion engine since its application in the transport sector.

Consumers have always placed a high value on dependability in choosing a car. But other preferences have loomed large at various moments in time. The oil price shocks of the 1970s seem to have marked the 1981 preference structure, with its emphasis on fuel economy (table 1.1). Six years later, however, fuel economy was of least importance to the consumer and price had, along with dependability, become the prime concern. In the latter half of the 1990s safety replaced both fuel economy and price as the second most important buying preference. This change in preference was accompanied by a rise in sales of SUVs and other large vehicles.

Despite the brief blip in consumer preferences for fuel economy, in terms of the trade-off between efficiency, power and pollution, consumers and producers alike have joined forces over this 20-year period in the

Table 1.1 Consumer automotive buying preferences

	Fuel economy	Dependability	Price	Quality	Safety
1981	43	32	14	4	9
1987	4	44	31	8	14
1996	7	35	11	19	29
2001	11	30	8	22	30

Source: Derived from US Office of Technology Policy (2003: 6).

pursuit of power. This is reflected in data from the US Environmental Protection Agency which show that since the 1980s horse power has increased by 84 per cent, “allowing vehicles to accelerate faster even though they have gotten heavier”, at the expense of fuel efficiency (Fischetti, 2002: 41–42). Emissions have thus remained a problem and, as automobile sales rose in the developing world and Eastern Europe, the internal-combustion engine came increasingly under fire in international milieux as a significant and growing source of environmental damage.

Rather than engine efficiency, emissions and energy concerns are thus driving the move away from the gasoline-powered internal-combustion engine. Through regulatory policies, tax incentives and financial support for R&D, attention was focused primarily in two directions, neither of which has produced the required magnitude of change. The electric vehicle floundered in the continued technological problems of battery storage and the consumer preference for rapid acceleration and refuelling (Neufville et al., 1996). Its successors, hybrid cars such as the Toyota Prius and Honda Insight, have only recently been commercialized and others only began to appear in 2005. Despite their newness, moreover, they are clearly an intermediary solution based on incremental improvements to older models. Alternative fuels such as ethanol are still in dispute and currently make only a small dent in the overall pollution problem, especially where they provide only 10 per cent of the fuel.

We have thus reached a classic point in the evolution of technological trajectories – the exhaustion of the current technological paradigm. Is the next wave of technological change upon us?

## Policies, promises and practices: The application of hydrogen fuel cells in the transport sector

Although a first working fuel cell was demonstrated by a Welsh scientist, Sir William Grove, in 1839, it was not applied for over a century. This contrasts with the internal combustion engine, whose principles were known in the seventeenth century and applied in the eighteenth century to pump water from coalmines. Not until some 200 years later, however, was it used to power a moving vehicle. But within only a few more decades, the ICE had become established as the dominant design in the automotive industry (fig. 1.2). While the genesis of modern fuel-cell technology and its application in the automotive industry have moved more quickly than was the case with the internal combustion engine, it is still too early to say whether it will emerge as the dominant design in motor vehicles.

Fuel cells reverse the long-known process of electrolysis, which uses energy to split water into its components. Instead they use a fuel supply to combine hydrogen and oxygen, thus generating an electric current. The first PEM fuel cell was developed in the 1950s by General Electric (GE) for the US space programme and provided electrical power on board the Gemini spacecraft in the 1960s. Thereafter, however, GE sold its PEM fuel-cell business and concentrated its work during the 1970s and 1980s on fuel cells with a phosphoric acid electrolyte, oriented towards stationary power. Phosphoric acid fuel cells were the preferred area for research on fuel-cell technology throughout this period, although some work on PEM fuel cells did continue, based initially on a Nafion membrane developed and patented by DuPont and applied in a variety of chemical manufacturing processes.<sup>16</sup>

Partly because of its potential for miniaturization and thus use in mobile equipment, the military maintained a residual interest in the PEM fuel cell. In the early 1980s Ballard, a Vancouver-based Canadian start-up then working on lithium batteries, won a Canadian Department of National Defence (DND) tender to produce a “low-cost” PEM fuel cell that could run on impure hydrogen produced by reforming a liquid fuel like methanol (Koppel, 1999: 63–64). The first Ballard cell was based on the old GE fuel cell, but replaced its polystyrene resin membrane with a Nafion membrane and the GE flow-field plates made of niobium by sheets of graphite with carefully machined fine grooves on the electrode side of each plate (*ibid.*: 77). Both of these innovations and the development of a special manifold to distribute the gases (*ibid.*: 80) were then patented. In two years Ballard succeeded in developing an eight-cell stack that produced 130 watts, considerably higher than the 50–100 watts specified in the DND contract (*ibid.*: 86). By mid-1986 it had succeeded in creating a 12-stack version capable of producing 280 watts. The DND awarded Ballard a second contract for further development. If changing the flow-field design had quadrupled performance in the first phase of its development, finding a new membrane<sup>17</sup> would result in yet another major jump. Over the next five years Ballard built ever more powerful and smaller PEM fuel-cell stacks.

By 1993 the first Ballard fuel-cell bus was plying the streets of Vancouver and Daimler-Benz and Ballard had agreed on a joint venture, to which Daimler committed \$35 million over four years. In 1994 Daimler-Benz had its first New Electric Car (NECAR) on the road, a boxy cargo van whose passenger space was largely taken up by 12 stacks, collectively generating 50 kilowatts (kW) and producing 60 hp, and tanks holding compressed hydrogen. But technological progress was accelerating (*fig. 1.3*). Two years later, NECAR II had smaller, lighter stacks and could

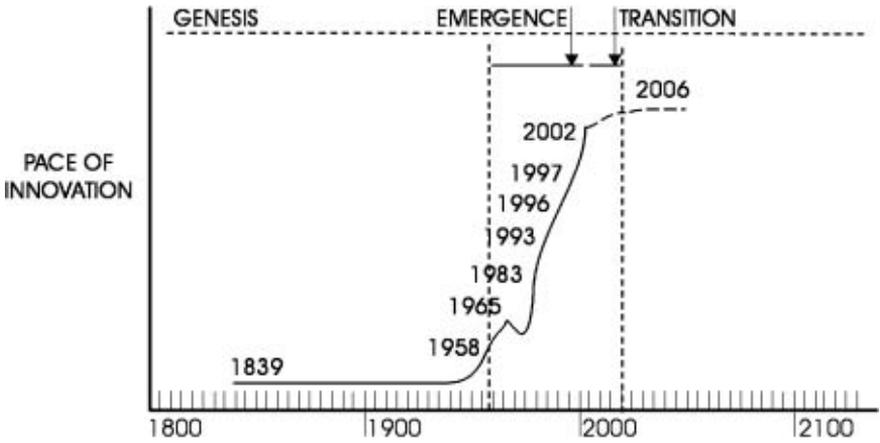


Figure 1.3 Development of the fuel-cell engine

go at 110 mph, and by November 2000 DaimlerChrysler's NECAR V was a five-passenger Mercedes-Benz A-class vehicle with a powerful 75 kW engine and an on-board methanol reformer. It produced no exhaust emissions.

#### *The turning-point: 1994–2002*

The year 1994 was a major turning-point in the emergence of the PEM fuel cell as the prime contender to replace the internal-combustion engine. The dramatic rise in patenting is one indicator. Normally, there is a considerable time lag between research and patenting. But an online search of the US Patent Office database reveals that the number of transport-related fuel-cell patents rose dramatically from 204 in the period 1991–1995 to 732 in the years 1996–2002.<sup>18</sup> Data provided by the US Office of Technology Policy (2003: 3, 23) similarly show a sharp rise in patenting activity in the “automotive fuel cell patent family”, from some 20 per year in 1994 to 60 in 1998 and 180 in 2001, and strong patenting activity in the “hydrogen storage patent family” from 1996 onward. The investments in research that led to this patenting activity accelerated the speed with which new technologies moved from the drawing boards to prototypes, and augured well for the pace at which technological solutions might be found for existing problems.

Over these years every major automobile company announced programmes to develop fuel-cell vehicles and built alliances and/or created the in-house capability to do so. In 1997 Daimler-Benz took a 25 per cent stake in Ballard and was later joined by Ford, with a 13.5 per cent

share, and by Shell working to develop the fuel for new generations of fuel-cell cars. General Motors and Toyota, partners in electric car development, began working on a fuel-cell car in 1999 and GM later also developed a partnership with Millennium Cell for this purpose. Other automobile companies also joined the race: Honda and Nissan, working initially with Ballard fuel-cell stacks; Hyundai and BMW, using stacks produced by International Fuel Cells; and Renault and Fiat, working closely with Nuvera Fuel Cells.

A proven concept, performance capabilities, the accelerating pace of technological change, competition among rivals and a shortening time horizon all played a role in the rapid turnaround from scepticism to action on the part of automobile manufacturers. By 1996 the concept of a PEM fuel-cell engine had been proved, and the speed with which the Ballard-DaimlerChrysler-Ford alliance moved down its learning curve was simply remarkable. In addition to DaimlerChrysler, other auto makers were moving rapidly down their learning curves and engaging in systems integration. In a relatively short time Honda, for example, moved from its first FCV, a hydrogen-fuelled vehicle with energy stored in metal hydrides, motor power of 49 kW and the ability to seat only two passengers, to its FCV4 in 2000 – a hydrogen-fuelled car with hydrogen stored under high pressure in tanks at 35 MPa, motor power of 60 kW and the ability to seat four people and still have space for luggage. Both vehicles used Ballard fuel-cell stacks. Unlike the prototypes and concept cars of a few years earlier, limited road testing of this new generation of FCVs – an important step towards commercial production – was envisaged within a few years.

Little doubt remained that fuel cells powered by hydrogen or methanol would be far more energy efficient than gasoline cars and also more environmentally benign (US Office of Technology Policy, 2003; Ogden, Williams and Larson, 2004). It increasingly became evident, moreover, that they would be able to match the performance of internal-combustion engines; and an ultra-capacitor to store energy, already commercially available on Honda cars, would provide the extra power for starts and passing that had turned consumers away from traditional electric cars. With fewer moving parts, the fuel-cell engine would outlive the internal-combustion engine and have the added advantages of an electric drive train to deliver power to the wheels and software to provide the car with “drive by wire” control that eliminates the need for the mechanical systems traditionally used for steering, power and braking (Williams, 1994; Swoboda, 2002: 10).<sup>19</sup>

By the late 1990s the main question was no longer whether fuel cells could supplant the internal-combustion engine as the dominant design in the automobile industry, but rather when this would be likely to occur.

Although some articles continued to place the time horizon for commercialization far into the future (Freedman, 2002), most writers in the field had begun to talk of 2020 (US Office of Technology Policy, 2003), and as the millennium drew to a close some were suggesting that PEM fuel-cell vehicles would be commercialized as early as 2010. That allowed very little time for auto makers to learn, innovate, design and mass manufacture such a radically new product.

Was this hype or reality? Like other research-intensive industries of the 1960s and 1970s, as the pace of technological change accelerated, so too did the pressure to form alliances through which consensus on a dominant design and common standards could be forged and systems integration could be rapidly pursued. Two broad alliances emerged in this period.<sup>20</sup> Fundamentally different in construction, the first was centred on Ballard and modelled itself on a structure existing in the information and technology sector, where networks formed around rival component solutions and their producers, such as Intel in microprocessors or Microsoft in software. The second centred on General Motors and adopted a design typical of the biopharmaceutical sector, where large final-assembly firms are at the core of networks composed of smaller, vertically integrated companies. Rival networks such as these characterized the emergence of a dominant design in the development of the VCR, computer disks and a variety of telecommunications equipment, but the timeframe, infrastructure investments and costs to the consumer and society were far lower than they are likely to be in the development of a fuel-cell vehicle.

Within these alliances, all producers remained flexible in the types of fuel cells they produced, tailoring these to their customers. Ballard Power Systems, for example, initially focused on direct-methanol PEM fuel-cell technology that would not require an on-board reformer, but also supplied hydrogen fuel cells to its clients on demand.<sup>21</sup> Nuvera Fuel Cells, which estimated that it would still take some 20 years before a hydrogen society came into existence, stressed that “Until that time, we must turn to alternative innovations to solve the world’s growing energy demand. Hydrocarbon-fuelled fuel-cell systems offer one such solution.”<sup>22</sup> Nonetheless, although specialized in gasoline-fuelled FCs with metallic stack architecture, Nuvera worked with its partners and customers to produce other types of fuel cells as well. The absence of a dominant design as fuel-cell technologies began to emerge did not then seem to be a serious impediment to realizing a commercializable FCV.

Each of these alliances pushed forward its own agenda with regard to several critical choices. Paramount among these was the choice of fuel, as it is linked to the choice of engines, fuel-cell design and the need for either an on-board reformer or an on-board fuel storage system.<sup>23</sup> Costs, technological complexity, regulatory pressures and time to market are

major factors affecting trade-offs here. But the choice of fuel is also systems embedded, and the availability of infrastructure and social acceptance as well as the habits and practices of auto manufacturers and oil producers and refiners can be expected to shape the parameters within which a decision about fuel will be taken. As DaimlerChrysler's vice president for research and development argued, "The most important unresolved issue with fuel cell vehicles is not the fuel cell, it's the fuel" (*Financial Post*, 2002).

The choice of fuel in this period was mainly focused on three alternatives: hydrogen, methanol and gasoline.<sup>24</sup> Curiously, the initial choice of fuel by core members of the two broad alliances whose influence was paramount in shaping competitive pressures at the time has since changed. Chrysler, for example, began with gasoline as its preferred fuel. Following its merger with Daimler-Benz, however, it switched to methanol, and in parallel began work on the development of a more innovative technology based on sodium borohydride, better known in its laundry powder version as borax.<sup>25</sup> GM, which began with hydrogen and a radically new car concept, became the major proponent of gasoline fuel cells (Truett, 2001) and characterized its 1999 partnership with Toyota and Exxon-Mobile as a means "to speed the development of a clean hydrocarbon fuel for FCVs [and] an important bridge to a pure hydrogen infrastructure".<sup>26</sup> Some might question, however, whether continued use of hydrocarbon-based fuels is a bridge or a barrier to a radically new technology.

Hydrogen faced the greatest hurdles in establishing itself at the outset as the preferred fuel for FCVs. For example, it had an image problem to overcome, as some still emphasize its explosive potential if stored as a gas. But a number of solutions to the distribution and on-board storage problems were already commercially available. These derived from earlier experiences with liquefied and compressed natural gas (LNG and CNG), and demonstrated the safety of hydrogen in these two forms.

Some hydrogen-powered fuel-cell vehicle prototypes stored hydrogen on board under high pressure in canisters made of lightweight, high-strength material such as aluminium wrapped with carbon fibre. Hydrogen-powered FCVs are environmentally friendly, but the complementary technologies needed to ensure well-to-wheel environmental sustainability, cost-efficient hydrogen production and the infrastructure for delivering hydrogen at the pump or to the home were in their infancy. The infrastructure costs of building a distribution network from scratch, moreover, were very high.<sup>27</sup>

Towards the end of the 1990s public-private sector alliances emerged as the basis for concerted efforts to develop the necessary fuelling infrastructure. One of these was the California Fuel Cell Partnership (CFCP)

in the United States. DaimlerChrysler and its partners were among the founding members in April 1999; 18 months later, GM and Toyota joined. Another was the European Union's Fifth Framework Programme. The Ecological City Transport System project, ECTOS, began in March 2001 and ran until February 2005. It involved "creating a hydrogen infrastructure and demonstrating fuel cell buses in Iceland's capital, Reykjavik, in the first large-scale, real-world trial of converting to a hydrogen infrastructure" (US Office of Technology Policy, 2003: 53).<sup>28</sup> Given the need for more research and testing, while most acknowledged that hydrogen fuel-cell vehicles were the wave of the future, many turned to intermediate solutions to deal with the fuel and fuelling problems.

Methanol, derived from natural gas, represented a middle road. It has a higher octane number, allowing for higher compression ratios and hence greater thermal efficiency compared to gasoline engines. Its well-to-wheel energy consumption is also lower than that of gasoline, although tiny amounts of carbon monoxide and oxides of nitrogen are produced by the operation of the reformer and small amounts of evaporative emission may come from the fuel tank (International Energy Agency, 1999: 23–27; Williams, 1994: 24). Many of the complementary technologies, such as processes for the production of methanol from natural gas and the distribution of natural gas, already exist, and a number of countries with important automotive markets have significant natural gas vehicle fleets.<sup>29</sup> Thus countries that "have natural gas distribution grids can introduce it as a vehicle fuel relatively easily, but nations without such infrastructures will find them very costly to establish" (International Energy Agency, 1999: 23). The choice of methanol, however, will lead to heavy investment costs in countries where natural gas is not readily available, the installed methanol production capacity is weak and the distribution network limited or non-existent – a strong negative factor for many developing countries.<sup>30</sup>

Considerable progress has been made in using methanol to power fuel cells. Small on-board methanol reformers, for example, are already installed in test vehicles and high-compression canisters for on-board storage have been developed and tested. Methanol is also a close substitute for gasoline in the pattern of refuelling and the distance between refuelling stops, thus catering to current consumer habits and practices.<sup>31</sup> The methanol option also continues the pattern of dependence on hydrocarbons, and fails to achieve the zero-emission promise of HFCVs from well to wheel.

From the environmental perspective, the life cycle of gasoline is even less optimal. Nor does the choice of gasoline improve fuel security in the short to medium term,<sup>32</sup> unless it is accompanied by expanded exploration and development.<sup>33</sup> However, by minimizing the problems of both

systemic embeddedness in an existing fuel-distribution network and social embeddedness in the preference of both oil companies and consumers to preserve older products, existing infrastructure and traditional habits and practices with respect to rapid refuelling at a multitude of existing fuelling stations, gasoline was the least disruptive of the choices. If speed to market is the goal, then a gasoline-powered fuel-cell car might also give the appearance of being a rational choice, at least in the short term. But appearances in the GM case were deceiving, and after years of trying to develop a small on-board gasoline reformer, General Motors seems to have abandoned this option – but not before Nissan and Renault followed suit, fearing that a gasoline-powered fuel-cell car could become the American standard, at least in the medium term (Associated Press, 2001).

While gasoline is no longer high up on the list of fuelling choices for fuel-cell engines, this is not because a consensus had emerged on the dominant design for a hydrogen fuel-cell vehicle. On the contrary, by the turn of the century HFCVs were being pushed off centre stage and gasoline was showing signs of a comeback, this time as part of the impact that hybrid vehicles were beginning to have on the nature of competition in the industry and the matrix of choices available to enhance energy efficiency and reduce greenhouse gases (GHGs).

From the mid-1980s to the mid-1990s Toyota slowly expanded its research on electric batteries and motors. This is reflected in rising patenting levels in this family of activity, which rose from under 25 in the pre-1994 period to 50 in the year 2000 (Kuroki and Yarime, 2003).<sup>34</sup> Triggered by California's<sup>35</sup> effort to reduce pollution levels quickly through the adoption of stringent emissions rules that no existing internal-combustion engine could meet, Toyota's research on hybrid vehicles moved into high gear. From under 30 in 1994, the number of Toyota hybrid patents jumped to nearly 200 in 2000 (*ibid.*). In 1997 Toyota introduced the first gasoline-electric hybrid vehicle. Its performance characteristics would not have tempted an American buyer any more than earlier electric motors had done. This early version of the Prius was sold only in Japan, but four years later Toyota was ready with a car that matched the preferences of its American clientele.

Once introduced into the American market in 2001, the hybrid vehicle changed the rules of the game. Able to meet emissions standards of the future, with the performance characteristics of pure gasoline engines and the advantage of substantial fuel economy, the Prius became the car to beat. Within a year Honda's version of a hybrid went on sale in the United States, followed by Ford and others.<sup>36</sup> Wedded to heavy, gas-guzzling sport utility vehicles (SUVs), to Americans the hybrids seemed like a godsend in a period of rising oil prices.

This is the context within which increasing R&D investment by American and Japanese auto companies in the period from 1996 to 2001 must be interpreted. In the United States, investment by the formerly sluggish automobile industry amounted to some \$18.4 billion in R&D in 1997, higher than any other manufacturing sector in that country (US Office of Technology Policy, 2003: 3), and R&D investments by Japanese vehicle makers rose from an average of US\$11.8 billion in the period 1990–1995 to \$14.7 billion in 1996–2001 (ibid.: 33). Governments also announced programmes of R&D funding for the development of FCVs and supported consortia to work on complementary technological systems. The US government, for example, established its Freedom CAR Partnership between the Department of Energy and the US Council for Automotive Research composed of General Motors, Ford and Daimler-Chrysler. Although its stated primary objective was to promote the development of hydrogen as a fuel for cars and trucks, much of the research undertaken through this programme addressed improvements in existing ICE-based technologies that would increase fuel economy and engine performance, and the new ICE programmes put in place during this period will not end until 2012/2013 (Truett, 2001: 39). In Japan, as seen above, research was heavily focused on the development of a strong electric motor capability, and this became the basis for the lead taken by Toyota in the commercialization of hybrid cars later in the decade.

### *The debate continues*

At issue in determining the pace with which a dominant design emerges in a disruptive technology are the interests and preferences of both producers and consumers, the systems embeddedness of the technology and the role of public policies in shaping the parameters within which these decisions will be made. The interplay between government and business has been particularly important in shaping the process of arbitrage between innovation and the preservation of established ways of doing things that has been taking place with regard to HFCVs in the first decade of the twenty-first century. As Carlota Perez (2002: 26) pointed out:

Each technological revolution, originally received as a bright new set of opportunities, is soon recognized as a threat to the established way of doing things in firms, institutions and society at large ... while competitive forces, profit seeking and survival pressures help diffuse the changes in the economy, the wider social and institutional spheres where change is also needed are held back by inertia stemming from routine, ideology and vested interests.

Under these circumstances it would be highly unusual if technological trajectories were strictly linear. The current period is no exception. By

2002 both government and business had become increasingly outspoken in dampening down the expectation of a rapid move to HFCVs. GM's top management pushed openly for incremental innovation along established trajectories and Elizabeth Lowery, GM's vice president for environment and energy, told the Globe 2002 Conference on Business and Environment that "gas and diesel powered cars would not disappear for another 50 years". Her explanation for this far-distant frontier was a lack of current consumer demand for alternatives to fossil-fuel-powered vehicles: "customers don't want to make trade offs" (*Financial Post*, 2002). But as innovation-based competition across a wide range of consumer goods illustrates, consumer tastes are not immutable.

The next year, the European Union's High Level Group created with a view to formulating "a collective vision on the contribution that hydrogen and fuel cells could make to the realisation of sustainable energy systems in the future" (European Union, 2003: 5) reported in favour of short- and medium-term efforts to "improve the efficiency of fossil-based technologies and the quality of fossil-based liquid fuels" (*ibid.*: 21–22). In June 2003, at the EU conference on "The Hydrogen Economy. A Bridge to Sustainable Energy" at which this report was launched, the United States and European Union agreed to collaborate for the purpose of accelerating the development of hydrogen as an energy source. At the same time, however, conference documents reflected a subtle shift in the timeframe within which it was expected that commercialization of hydrogen fuel cells would take place. Moreover, although President Bush had announced an increase in funding for the hydrogen economy in his State of the Union message in January 2003, of the \$1.7 billion in funding over the next five years only \$720 million would involve new funding (*ibid.*: 5).<sup>37</sup> The US-inspired International Partnership for the Hydrogen Economy (IPHE), which held its first ministerial meeting in November 2003, was similarly off to a slow start in tackling the key issues that appeared to be holding back the emergence of hydrogen as the new energy source and the application of HFCVs in the transport sector. Over the following 18 months its focus was on the development of common codes and standards to facilitate a transition and the preparation of an IPHE roadmap to shape that process in a coordinated manner. But if the problems were more fundamental and required major investments in frontier research, the IPHE partnership did not appear to be the vehicle through which this would be done.

The European Union's Sixth Framework Programme reflected a similar view of the timeframe and activities needed to reach the hydrogen economy. Within this programme the focus was on the production of cleaner fuels, though not necessarily hydrogen, and on early preparatory work in the organization of fuelling distribution systems. Most of the funds were thus spent on producing clean hydrogen and rich synthesis

gas from methanol, preparing for the hydrogen economy by using the existing natural gas distribution system, studying supply options across Europe's regions, setting standards, engaging in major fleet demonstration projects and supporting the Hydrogen Technology Platform Secretariat. Of the subprogrammes relevant to the hydrogen economy, only "hydrogen end use" involved new research: €5 million for work on a direct-hydrogen internal-combustion engine, €12.6 million in research funding for solid oxide fuel cells used in stationary power plants, €8.8 million for power-train development for direct HFCVs in cars and auxiliary power units in trucks and €5 million to study stack designs and high-temperature polymer-electrolyte-membrane fuel cells.

In 1994 an article in MIT's *Technology Review* noted that "Serious pursuit of the fuel-car option will require a major redirection of U.S. automotive R&D" (Williams, 1994: 28). Since then, the data show that governments continue to underfund research on hydrogen fuels and fuel cells, and have done remarkably little to change incentive structures for producers or consumers. This has sent very strong signals to the automobile companies that real competition, for the foreseeable future, will be in established markets. Auto companies such as Ford thus emphasize that they are "actively engaged in the development of four promising future alternatives to today's gasoline engines including clean diesels, gasoline-electric hybrids, hydrogen internal combustion" and hydrogen fuel-cell vehicles (Ford, 2005). Three of the four alternatives preserve the internal-combustion engine as the core technology and two support continued movement down a hydrocarbon-based fuel trajectory. Similarly, in April 2004 GM and Ford announced a \$720 million investment to design and build an all-new, fuel-saving, six-speed front-wheel-drive automatic transmission which "is expected to offer up to four percent improvement in fuel economy over traditional 4-speed automatic transmissions available in today's front-wheel-drive cars" (General Motors, 2004). If figures recently released by the US Environmental Protection Agency (EPA) on fuel economy trends in the United States are to be believed, model year 2005 vehicles were estimated to average 21.0 miles per gallon (mpg), which is 5 per cent below the fleet average fuel economy peak value of 22.1 mpg reached in 1987 (US Environmental Protection Agency, 2005). The new GM-Ford transmission, even if it does function as expected, will not even return average fuel economy figures to those of nearly 20 years ago.

With attention directed elsewhere, the pace at which a dominant design is emerging in the development of hydrogen fuel-cell vehicles appears to have slowed down; but for how long?

Many of today's debates are reminiscent of those that took place in the early decades of the gasoline-powered ICE (discussed earlier). The qual-

ity and ability to deliver the hydrogen that would be needed if HFCVs were to take off are one such example. Hydrogen proponents, however, see arguments over infrastructure as red herrings. Ballard's former CEO, Denis Campbell, noted that "U.S. industry currently produces 50 million to 60 million tons of hydrogen per year, so it's not like there's no expertise in handling hydrogen out there" (Ashley, 2005: 57). But Herbert Kohler, vice president of body and power-train research at Daimler-Chrysler, argues that "Fifty to 60 percent of the problems we have with our fuel cells arise from impurities in the hydrogen we buy from industry" (*ibid.*). Looking back to the early days of the ICE-powered automobile, however, the developed world seems particularly well endowed with hydrogen refuelling stations, some 60–70 of which are operating in Japan, the European Union and the United States at a point in time when there are no commercial vehicles yet on the road. Is the cost of new fuelling infrastructure way beyond our means, or is it, as Ballard's CEO pointed out, considerably less than what is being spent on infrastructure by ICT firms around the world?

Business scepticism about the speed with which some of the remaining technical problems will be resolved, such as reducing the costs of hydrogen storage, curiously echoes the situation facing auto makers in the 1920s, which found themselves up against the traditional research habits and practices of oil companies that continued to focus on increasing the quantity of gasoline being produced rather than improving its quality. With regard to the high costs of on-board hydrogen storage, Bill Reinert, national manager for Toyota's advanced technology group, was quoted as saying: "I'm less than hopeful about reducing costs sufficiently and I'm quite pessimistic about solving hydrogen storage issues ... high volume production could be 25 years off" (*ibid.*: 52). Yet both government and business are investing far less than is needed to deal with this problem. In January 2005, for example, General Motors and the US government's Sandia National Laboratories launched a programme to develop metal hydride storage systems based on sodium aluminium hydride. Only US\$10 million is to be invested in this research over a four-year period: this is too little, and perhaps even too late. Delft University and the Colorado School of Mines have already developed a lab version of a hydrogen hydrate storage system in which hydrogen is trapped in molecular-size cavities in ice and a "promoter" chemical, tetrahydrofuran, stabilizes the gas hydrate under far less extreme pressure than is currently the case: 1,450 versus 36,000 psi. Theoretically this should make possible the storage of 6 kg of hydrogen in about 120 kg (120 litres) of water, increasing the range of fuel-cell vehicles to that of gasoline-powered internal-combustion engines and substantially reducing costs (*ibid.*: 55).

There are also a number of new technologies under development that appear to have the potential to cut costs dramatically. Hitachi Maxwell, for example:

used technology for synthesizing ultra-small particulate magnets – technology created during the company’s development of magnetic tape – to uniformly deposit oxide particles a mere one nanometer in diameter on a substrate . . . when the deposited particles reach one nanometer in size, their reactivity increases dramatically. Consequently, if this new catalytic material is used in combination with platinum as the catalyst in a fuel cell, for example, the catalyst performs just as well as a pure platinum catalyst even though the amount of rare metal used has been decreased. (*Japan Journal*, 2005)

Poly Fuel, a small company in Mountain View, California, announced the creation of a hydrocarbon polymer membrane that reportedly cut in half the price of DuPont’s Nafion material, while 3M has boosted catalytic activity by creating nano-textured membrane surfaces covered with tiny columns (Ashley, 2005: 53–54).

## Building consensus/setting priorities

While clearly there remain many problems to be solved in producing, distributing and storing hydrogen, it is unclear whether any of these requires a major scientific breakthrough.<sup>38</sup> If they are more like the “knocking” problem that reduced the power and reliability of the internal-combustion engine early in its history, it should be possible to refocus research efforts on the issue of consistency in the production of high-grade hydrogen. As pure hydrogen was not required for earlier industrial uses, a change in the habits and practices of hydrogen producers will be needed.

What we find, however, is that although research on hydrogen fuel and fuelling problems is still continuing and research funding is once again on the rise, the focus on fuels in a period of dramatically high oil prices is being redefined away from critical hydrogen issues and towards short- and medium-term considerations by both business and government. Research funding for “cleaner” hydrocarbon-based fuels has thus increased, and investments in natural gas production and infrastructure are growing. To compensate for the relatively limited contribution of these initiatives to overall pollution abatement, the range of acceptable fuels has been widened to include alternatives, such as ethanol and biodiesel, for use in modified internal-combustion engines, making the ICE engine less environmentally damaging. The need to reduce pollutants in the environment

further also led to the introduction of government-funded incentives to stimulate the purchase of hybrid vehicles; but neither higher taxes on gasoline nor higher insurance premiums on SUVs were introduced as part of a coherent package of incentives that might change existing consumption patterns. Instead, competitive pressures are reinforcing efforts to extend traditional technologies by stimulating the rapid entry of newcomers into the market for hybrid cars and focusing attention on the need to bring out hybrid SUVs with the performance characteristics of the originals. As auto companies move down this alternative trajectory, they make it easier for consumers to hold on to old habits and practices and salve their consciences by buying green.

In terms of priority setting in both the North and the South, this review of options raises a number of critical questions.<sup>39</sup> Should we embark on building hydrogen fuelling stations now, or should we wait until new complementary reforming or electrolysis technologies are available to use the natural gas, water and electricity that already come into homes and workplaces, thus saving considerably on investments in infrastructure? Who will make such decisions, and how will they be made? If we do take this giant step forward into a hydrogen economy, what kinds of hydrogen storage systems, especially in vehicles, would be socially acceptable? One possible future scenario involves research currently under way on the absorption of hydrogen into solid compounds such as metal hydrides or in nanotubes.<sup>40</sup> But these technologies are not yet proven. Should we thus adopt an intermediary technology; and if we do attempt to reduce levels of pollution by using methanol or reformed gasoline, would this slow down the pace of realizing the ultimate goal of a hydrogen economy? And how would developing countries deal with the set of sequential new technological investments this would require?

Historically, moreover, rapid movement down the cost curve through standardization and the creation of economies of scale did not take place until a dominant design had emerged. Will the fuel-cell car be different? There are some indications that it will differ. For fuel-cell manufacturers, for example, dual-use technology – transport and stationary power – has been essential. Will it be easier to set standards and develop a dominant design for stationary power based on hydrogen fuel cells, and should this be pursued more vigorously than the application of hydrogen fuel cells in the transport sector? How would this reflect needs and priorities in the developing world?

With respect to fuel cells and the transport sector, however, we have far too little information on costs to evaluate this process. This gives rise to still other questions.

If the future is still “hydrogen” should we wait until all pieces of the system are in place, or do environmental considerations force us to take

action now? If the latter, how might we build a path today that does not compromise change in the future? With regard to the transport sector, can multiple solutions – gasoline, methanol and hydrogen, for example – coexist and be developed without wasteful investment? This is a problem of significant importance for current choices in the developing world. Would investment in gasoline reform in the North keep the market for petroleum buoyant and reduce incentives for change?

This book explores the many trade-offs to be considered in dealing with the above questions. In making choices in both North and South, three of these appear to be of particular importance in the country cases studied here:

- the cost and complexity of short-term versus longer-term horizons with respect to emissions reduction, energy security and infrastructure investment
- the impact of these choices on industry structure, competition and prices
- the incentives and constraints that present choices will create for capacity building which bridges the gap between development and global change, and for innovation in the future.

Policies will clearly have a major impact in shaping the parameters within which the choices between trade-offs will be made. Given the social, economic and environmental consequences that flow from each of these choices, dialogue between stakeholders will be needed to build awareness of the potential consequences. A dialogue of sorts has developed within the European Union as it builds its hydrogen platform, but the dominant voices in the dialogue are reluctant to champion radical change. For this to take place, governments in the North will have to take a more proactive stance in “promoting the new” and create the kind of “public knowledge goods” that have largely been missing in the rapid development of alliances and high rate of patenting. A better understanding of costs, standardized testing procedures and vetted empirical studies are the foundations upon which serious social reflection and consensus building can be created.

## Notes

1. Carlota Perez (2002: 30) divides this phase into two: the full constellation of new industries, technology systems and infrastructure, followed by the full expansion of innovation and market potential deriving from the technological revolution.
2. Michael Best (2001: 133) has distinguished four technological periods characterized by diminishing critical size dimensions: the mechanical, electrical, electronic and nano-levels (ranging from 10 to  $10^{-12}$  metres, megahertz to terahertz/sec or in photonics  $10^{-12}$  bits/sec).

3. For a more thorough discussion of new-wave technologies and their impact on technological catch-up in developing countries, see Mytelka (2004).
4. The remainder of this section draws upon Mytelka (2003).
5. Indeed, “we routinely fly in airplanes the optimal designs of which are achieved by fairly ad hoc, trial-and-error processes because there are no theories of turbulence or compressibility adequate to determine optimal configurations in advance. Extensive testing and modification based upon test results are still required” (Rosenberg, 1982: 143).
6. The chemically based pharmaceutical industry was a latecomer in this process; much of the attention of biochemists and microbiologists in the 1920s and 1930s was, in fact, focused on hydrocarbon chemistry in the petroleum sector, and it was there that most innovations took place. Catalytic cracking in a fully continuous flow process, for example, drew together five of the major oil companies, two process technology firms and the set of German chemical companies which formed the IG Farben cartel into a collaborative R&D project that Chris Freeman (1982: 62) describes as “one of the largest single programmes before the atom bomb”.
7. All countries that are members of the World Trade Organization (WTO) are obliged to implement its Trade Related Aspects of Intellectual Property (TRIPS) agreement, with only a few years’ grace for developing countries.
8. See, for example, the large number of such intermediaries created by the European Commission to stimulate research, innovation and competitiveness of European industries growing out of new-wave technologies (Mytelka, 2001).
9. Eventually it might be possible to develop a formal model of this approach. For the moment, however, it is used heuristically as the analytical framework in which to analyse the factors and forces affecting the pace at which technological change is taking place in the development and diffusion of fuel-cell technology in the automotive industry.
10. These included synchronized transmission for easier gear shifting, air-cooled engines, the Ricardo cylinder head, the mechanical fuel pump and the automatic choke.
11. Over the next decade, the General Motors Corporation (GM) took over the Olds Motor Company, the Oakland Motor Company, Cadillac and the Chevrolet Motor Company. It integrated backwards with the acquisition of Fischer Body and created an in-house research group (Chandler, 1964).
12. In the early 1920s Harry Ricardo had led a study that identified tetraethyl lead as a suppressant of knocking. His engineering consultancy firm also noted, as early as 1923, that ethyl alcohol was in some respects a better fuel and could be produced using renewable resources, thus solving the problem of future gasoline shortages as well as reducing pollution. See Compton (1982).
13. This was done through the US policy of federal aid to the states, initiated in 1916, and through annual registration fees and taxes on motor vehicles and motor fuel.
14. The impact of this on the ability of the “big three” US firms to compete with the flexible production systems introduced by the Japanese became the subject of considerable attention in the 1980s, and led to the establishment of the CAMI (GM-Suzuki) and NUMMI (GM-Toyota) plants and the link between Ford and Mazda (Womak, Jones and Roos, 1990).
15. Most of these systems were first innovated in the late 1920s in mechanical form and later updated electronically.
16. Nafion was a polymer developed by DuPont and used in chemical processes such as industrial-scale electrolysis of sodium chloride to produce chlorine and chlor-alkali (Yarime, 2003).
17. Initially this involved working with Dow Chemicals on a membrane it was developing, and in the 1990s creating an in-house team to develop a proprietary membrane of its own.

18. For a detailed analysis of patenting on electric, hybrid and fuel-cell technologies by Japanese automobile manufacturers, see chapter 10 in this volume.
19. “The Autonomy”, GM’s concept car presented in Detroit in 2002, was highly innovative in its design and showed the large number of new possibilities if “form follows function”; see *The Economist* (2002).
20. Other alliances, such as that between Hyundai and its partners, are too small to affect this process and have tended to ally with one or the other of these two broad alliances in dealing with these major choices.
21. See the Ballard Power Systems website at [www.ballard.com](http://www.ballard.com).
22. Statement by Roberto Cordara, president and CEO, on the Nuvera website at [www.nuvera.com](http://www.nuvera.com).
23. A close linkage between fuel and engine type had also characterized the internal-combustion engine, but the development of the flex-fuel engine in Brazil and its diffusion have made it possible to refuel with a wide range of alternatives – gasoline, ethanol, other bio-based fuels and blends.
24. Others, such as the hydrogen-on-demand Natrium fuel-cell vehicle developed by DaimlerChrysler using borax, were also in the pipeline.
25. Step on the throttle and a 20 per cent solution of sodium borohydride “is pumped past a catalyst made of ruthenium. This strips the hydrogen out of the compound and feeds it to the vehicle’s fuel cell stack. The used slurry is then stored until it is time to refuel, when it is pumped out while a fresh batch is loaded” (*The Economist*, 2002). The reformer was built by Millennium Cell. The hydrogen-on-demand process eliminates on-board hydrogen storage and reduces dependency on fossil fuels. To the extent that it is widely available, it improves fuel security.
26. See [www.gm.com/company/gmability/adv\\_tech/700-partners/index.html](http://www.gm.com/company/gmability/adv_tech/700-partners/index.html).
27. For an interesting business perspective to this problem, see chapter 4 in this volume.
28. Chapter 9 in this volume presents the results of this programme and current Icelandic policies with regard to the utilization of hydrogen in the transport sector.
29. Italy, Argentina, New Zealand, the Russian Federation and the United States (International Energy Agency, 1999; table 5.4 in this volume).
30. For a broader discussion of such choices see chapter 5 in this volume.
31. Although “the energy content of a unit volume of methanol is half that of gasoline, the fuel-cell car would be more than twice as efficient” (Williams, 1994: 23).
32. This is a particularly important consideration in a post-9/11 world or where the stabilization of oil prices depends on Saudi Arabia’s ability to increase oil output – something that is now being put into question.
33. Suggestions that this be carried out along the Californian coast or in the Arctic have been under fire until recently.
34. For a closer look at Toyota and other Japanese auto-manufacturer strategies, see chapter 10 in this volume.
35. Toyota was already a major player in the California auto market when the California Air Resources Board approved new emission standards requiring that 2 per cent of the vehicles offered for sale in the state in 1998 would have to be zero-emission, with this rising to 10 per cent by 2003.
36. On 24 December 2002 the *Wall St Journal* reported that GM and Toyota had decided to “gear up to produce hybrid gasoline-and-electric versions of sport utility vehicles and pick up trucks”. Clearly GM is still running scared after earlier efforts to produce and sell electric vehicles.
37. As of May 2005 the bill which would have authorized these funds had still not left the Senate for a conference between Senate and House of Representatives to harmonize the two versions of this bill (White House, 2005).

38. For other views on this issue see chapters 2 and 3 in this volume.
39. Many of these issues are explicitly discussed in chapters 2–4 and 13 in this volume.
40. Based on a discovery by Iijima, a Japanese scientist at NEC, and published in *Nature* in 1991.

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## 2

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# The Japanese strategy for R&D on fuel-cell technology and on-road verification test of fuel-cell vehicles

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### Introduction

The research, development and demonstration (RD&D) activities of PEM-type fuel cells and their applications in both stationary co-generation systems (the term co-generation systems is used to mean combined heat and power systems, usually abbreviated as CHP) and fuel-cell vehicles (FCVs) have been accelerated in the last five years in Japan, as a result of strong governmental interest and support as well as close cooperation between the government and related industries. These activities were initiated by a government committee, the Policy Study Group on Fuel Cell Commercialization, organized within the Ministry of Economy, Trade and Industry (METI) at the end of 1999. Based on studies in this committee, and its intermediate report issued in January 2001, all RD&D activities related to PEM fuel cells have been carried out along a recommended framework. The report clearly identified a timeline for long-term RD&D procedures and the roles of key players – government, industry and academia – in different development stages, i.e. basic preparation and verification, market initialization and take-off and diffusion in the market.

According to the recommendations of the study group, a new organization, the Fuel Cell Conference of Japan (FCCJ), was created by relevant industries in March 2001, and various programmes or activities have been planned and carried out through related organizations. Among them, verification tests of FCVs and FC co-generation systems in real-use

conditions started in 2002 and continued until March 2006. The outputs of these verification tests were analysed and results will be reflected in future plans to promote more market-oriented R&D together with basic research work to improve the reliability and lifetime of FC stacks.

This chapter begins by reporting on the key messages of committee reports, including the background, objectives and incentives of FC RD&D activities in Japan, the supporting organizations and stakeholder roles. It then outlines the FCV demonstration programme, including hydrogen supply stations and current demonstration results.

## Governmental initiatives and strategy for RD&D in FC technology

Worldwide enthusiastic promotion of RD&D in fuel-cell technologies is driven by issues related to road vehicles:

- local and regional environmental issues, especially air pollution by emissions
- global warming by CO<sub>2</sub> emissions
- energy security issues, dependence on oil resources and energy conservation
- severe international competition to keep the R&D initiative in PEMFC technology and its applications.

Among these drivers, there are some differences between regions. In Japan the last point – the need to build internationally competitive industries, especially in car and electric manufacturing – is important and draws the attention of politicians and government.

Prior to governmental actions, Japanese car makers had been developing and demonstrating various FCVs since 1996 (fig. 2.1), competing vigorously with the aggressive efforts of DaimlerChrysler. Stimulated by the worldwide interest in and activities related to FCVs, in December 1999 METI set up the Policy Study Group on FC Commercialization as an advisory committee on PEMFCs for automotive and stationary use for the director-general of the Agency of Natural Resources and Energy.

The group consists of representatives from universities, automobile, electric and electronic manufacturing industries, NGOs, the media, energy industries (electricity and gas utilities), industrial associations, related non-profit organizations, national institutes and membrane manufacturers. The objectives of the committee were identified as:

- to understand the current state of PEMFCs and its significance as a future technology
- to identify issues or barriers in promotion or commercialization

	1996	1997	1998	1999	2000	2001	2002
<b>Toyota</b>		<b>H2-FCHV (MH)</b> 	<b>Methanol reform. FCHV</b>		<b>H2-FCHV (H2 gas)</b>	 	
<b>Honda</b>			<b>H2-FCV (MH)</b>	 			<b>H2-FCV (H2 gas)</b>
<b>Nissan</b>			<b>Methanol reform. FCV</b>				<b>H2-FCV (H2 gas)</b>
<b>Mazda</b>			<b>H2-FCV (MH)</b>				<b>Methanol reform. FCV</b>
<b>Daihatsu</b>							<b>H2-FCV (H2 gas)</b>

Figure 2.1 Trends in FCV development in Japan

- to recommend strategy to overcome those issues, and propose RD&D policy for FCVs and FCs to the government.

After a year of intensive discussions and consulting with various related industries and organizations, including the US Department of Energy (DOE), DaimlerChrysler, General Motors and Ballard, the committee issued its intermediate report in January 2001, including a strategy for FC R&D in Japan. The report (METI, 2001) covers the following areas:

- merits and importance of FC realization and promotion, current status of technology level and its understanding, relevant industries (domestic and overseas) and governmental actions in the United States
- technical, economic and institutional barriers
- strategy to overcome those issues: identifying the role of government, industries and research areas, RD&D plans by development phases, short term to long term, and strategy by issue areas.

In spite of high expectations for FC commercialization, the actual technical and economic issues and barriers to its realization and promotion were well understood and identified in the report. These were summarized as:

- improvement of performance in the FC module
- cost reductions
- refuelling and supply systems (infrastructure)
- resource limitation and disposal
- software infrastructure, e.g. codes, standards and regulations
- social acceptance
- education of FC engineers.

For each category a detailed study was made and presented in the report, but the first three were most critical. As for required R&D, four areas were identified (fig. 2.2), among which the first two were considered most critical. These items are continually reviewed in the committee, and the results are reflected in the R&D support budget.

Naturally, the current high cost of FCs is regarded as one of the most serious barriers to commercialization, together with the required technical performance improvements (fig. 2.2) to narrow the gap between the current technology level and future targets (fig. 2.4). The committee also clarified the cost target for FC systems in FCVs to be competitive with conventional gasoline IC engines is ¥5,000/kW, which matches the US DOE target (\$45/kW).<sup>1</sup> This implies the necessity for further cost reductions by a factor of 100 times compared to the current cost. As for stationary use, the target cost is high compared to transport, although the required lifetime for stationary FCs is much longer. The target was estimated at ¥100,000 for 1 kW of output, which is a common target around

Considering technical difficulty and influence or significance at commercialization of pure Hydrogen FCVs, the following items are selected as urgent targets.

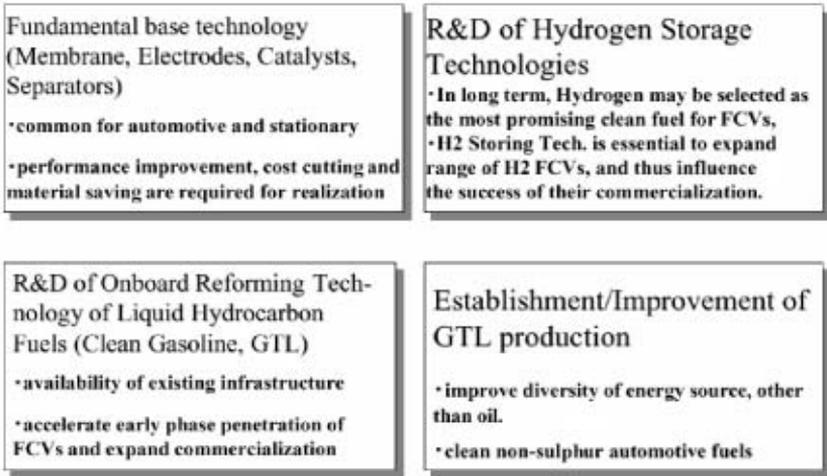


Figure 2.2 Targets of technology R&D of FCVs

the world. This implies a further cost reduction by a factor of 10, as well as further performance improvements in efficiency, reliability and longer lifetime.

After reviewing the current status, the METI (2001) report proposed a strategy to overcome barriers to FC commercialization. The strategy clearly identified the role of each key player, i.e. industry, government and research. It also identified short-term and long-term scenarios and three development phases (fig. 2.3). The approach can be summarized as:

- scenario setting for FC realization and RD&D planning through development phases and a short- to long-term strategy
- base preparation and technology verification (until 2005)
- initial introduction (2005–2010)
- penetration (after 2010)
- role of government, industry and research
  - industry: R&D for commercial products, market realization, establishment of a fuel supply infrastructure in the penetration phase
  - government and institutes: basic research, basic R&D, support for the establishment of new standards and regulations, support for infrastructure arrangements in the initial introduction phase
  - research and academic area: education, basic R&D.

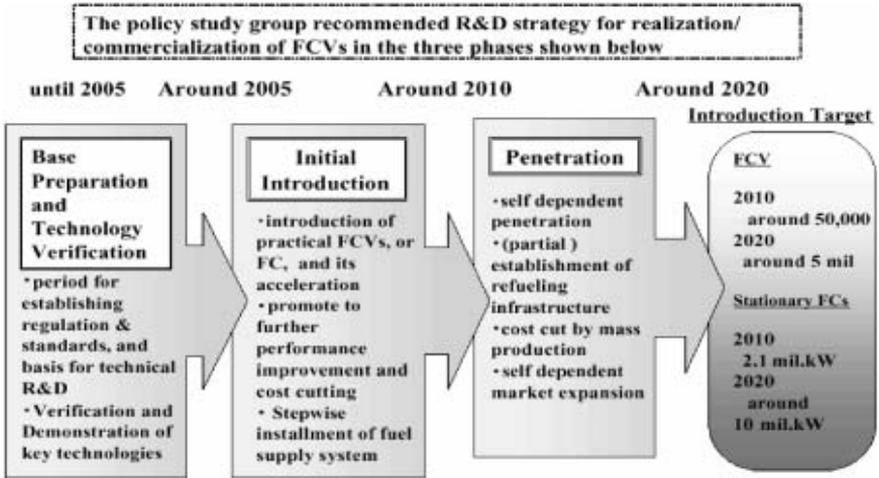


Figure 2.3 Scenario for commercialization and promotion of FCVs

As shown in figure 2.3, the first phase is regarded as the period for establishing the regulatory and technical R&D base, and demonstrating key technologies. The following activities were expected:

- establishment of test and evaluation methods for FC safety and reliability
- standardization and overview of existing regulations for FCVs
- education to strengthen human resources
- standardization of fuels
- fleet tests to verify technical and economic issues, and demonstration for public acceptance
- evaluation of well-to-wheel efficiencies and environmental impacts for available fuel paths
- fleet tests and demonstration of hydrogen stations.

Finally, the committee went so far as to set an “expected target of market introduction”, shown in table 2.1 (accumulated numbers), with the note that “this is an expected target to realize positive PEMFC market

Table 2.1 Expected target of market introduction

	2010	2020
FCVs	About 50,000	5 million
Stationary FCs	About 2.1 million kW	10 million kW

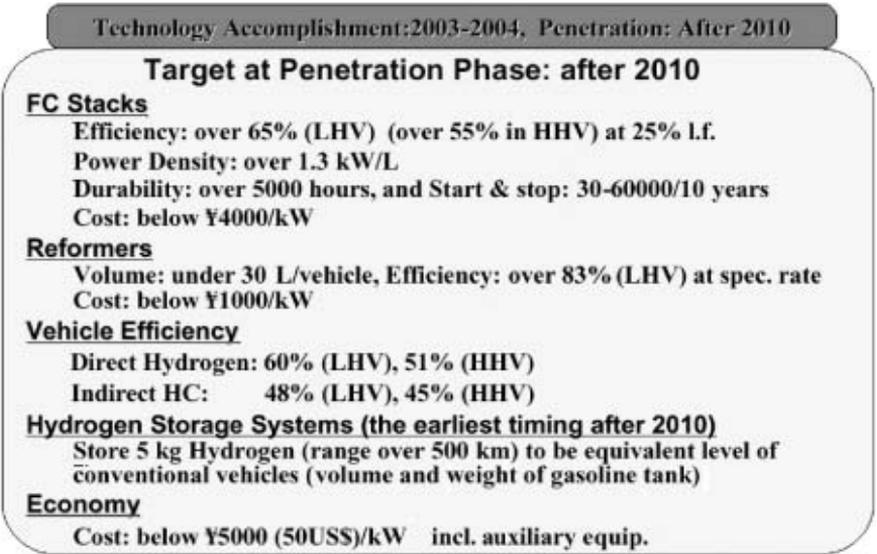


Figure 2.4 Target of FCV system performance and timing

introduction in appropriate time”. These very challenging and ambitious numbers became famous worldwide, stimulating a wide range of people who were interested in these technologies. However, it was well recognized that the target was quite ambitious and would be continually reviewed according to the status of development. The target numbers were authorized by the Energy Council, and introduced into national energy saving and CO<sub>2</sub> reduction guidelines. The required performance levels for cells for FCVs to be competitive with conventional ICE vehicles are summarized in figure 2.4.

### FCCJ activities by industry

In the METI (2001) report, the committee recommended establishing a new inter-industrial coordinating organization, the Fuel Cell Conference of Japan. This was founded in March 2001 by related industries, and became very active in carrying out the identified role of industry in promoting FC commercialization for both FCVs and stationary use. The objectives of the FCCJ are to identify specific issues in the commercialization and widespread use of FCs, submit policy proposals to the

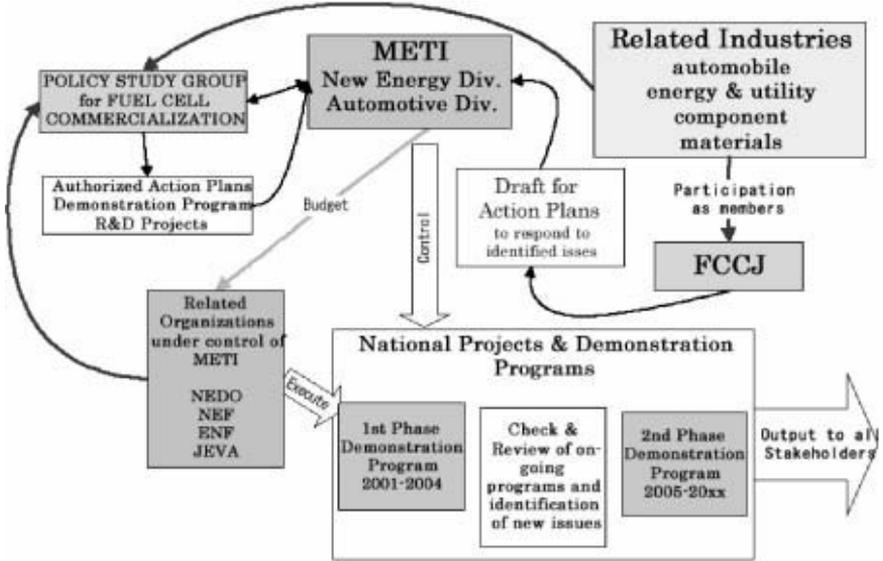


Figure 2.5 Relation and position of FCCJ

government to resolve the issues, and thus to contribute to FC commercialization and promotion, establishing FC industries in Japan.

Companies and industrial organizations active in developing FC technologies (e.g. fuel-cell, membrane and catalyst manufacturers, gas and electric utilities, automotive makers and petroleum companies) showed interest in joining the FCCJ. However, its scope was restricted to direct-hydrogen PEMFCs. DMFCs (direct-methanol FCs) were excluded because mobile DMFC was regarded as being almost in the market introduction phase.

Since then the FCCJ has kept in close and frequent contact with METI and its related bodies, including NEDO (the New Energy and Industrial Technology Development Organization), but has accepted no financial assistance from the government. The position and relation of the FCCJ with regard to METI and its subsidiary organizations are summarized in figure 2.5. The FCCJ works as a coordination body between activities and interests of both government and industry. The number of members of the FCCJ has increased rapidly, reflecting the strong interests and expectations of related industries (table 2.2).

Two working groups, the Technological Development Planning Working Group and the Commercialization and Public Acceptance Working Group, were organized within the FCCJ and work to propose, assist

Table 2.2 FCCJ membership (March 2006)

	March 2006	January 2001
Total number	131	99
Full members	84	65
Board members	23	21
General members	61	44
Associate members	34	21
Special members	13	13
Organizations	11	11
Personnel	2	2

and support government actions, reflecting industry’s requests to the government.

*Technological Development Planning Working Group*

Major achievements of this working group include:

- consolidated summarized requests to the national annual R&D budget regarding FCs and FCVs
- developed a roadmap for R&D of FC-related technologies, and reviewed constantly
- identified necessary conditions for FC promotion and commercialization
- investigated the foreign situation, especially US R&D activities
- communicated with outside organizations, e.g. the US DOE and the state of California.

An example of the roadmap for FCV technology is shown in figure 2.6, which is distributed by the policy study group.

*Commercialization and Public Acceptance Working Group*

This working group cooperated with outside organizations, and especially supported government tasks to identify and clear concerns in government-reviewed codes and regulations related to FC and FCV commercialization. The group consists of four subgroups: codes and standards, regulation and control, fuel selection and demonstration cooperation. Cooperating with government, the FCCJ regulation and control subgroup identified 28 concerns to be defined and reviewed by corresponding agencies. As a result, the government decided to review the identified regulations and solve the problems, by either revision or modification of interpretation of the regulations, by the end of 2003 in order to prepare for FCV commercial use (via a leasing system) from 2005,

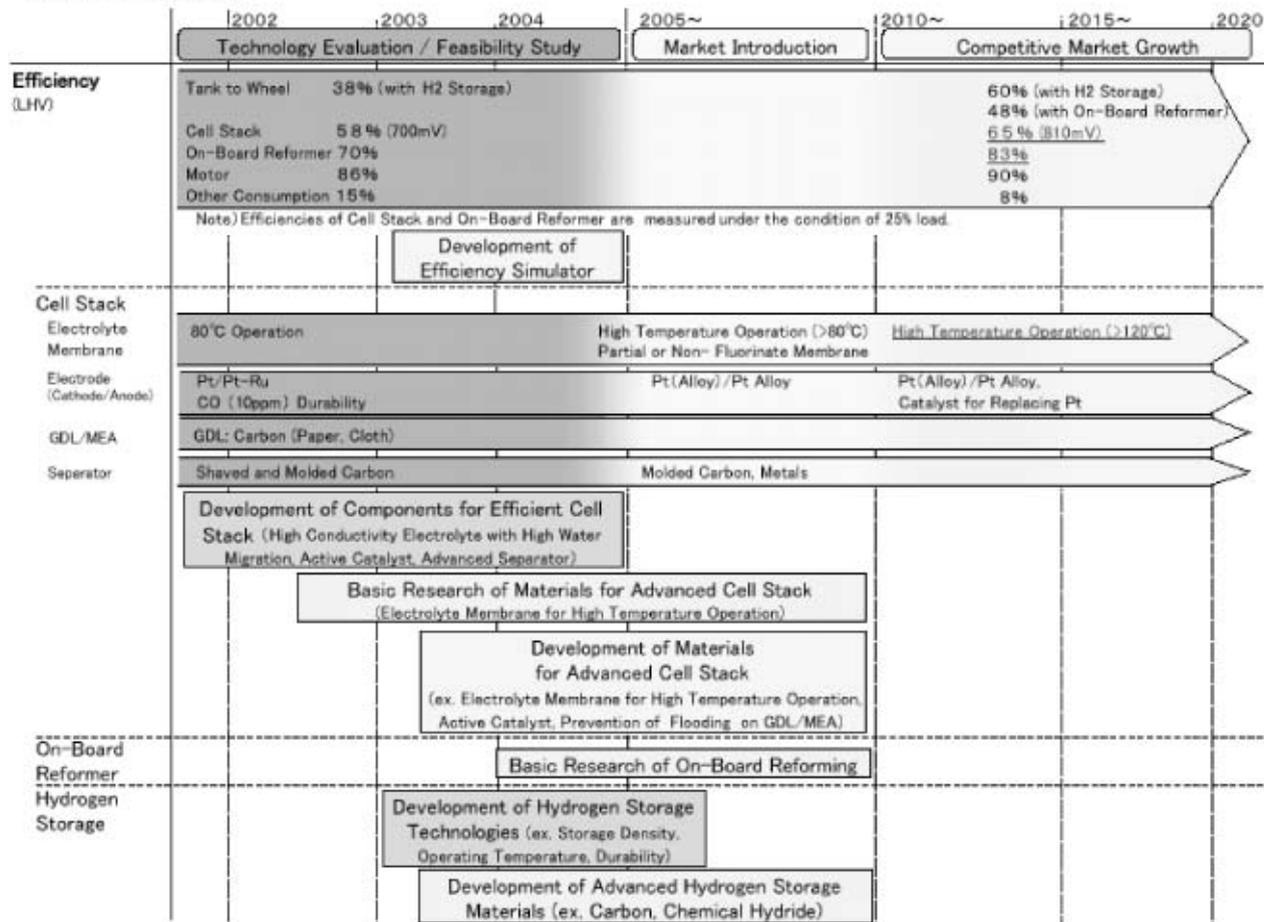


Figure 2.6 Roadmap for R&D of FCV technology

the METI FCV and hydrogen station demonstration project from 2003 and the initial market introduction of small co-generation units using FC stacks from 2005. This WG has also cooperated with actual operational organizations in verification tests continuously over the last five years.

Major outcomes of the working group can be summarized as follows.

- Requesting the government to review regulations that may hinder FCV commercialization.
  - Submission to the vice ministers meeting (02/3.29).
  - Submission to “request to review 6 articles, 28 items related to FCV promotion” to the governmental coordination meetings across ministries regarding FCs.
  - In response to this request, the cabinet secretary announced the review programme.
  - Cooperation to arrange industries’ organization to respond to the review.
- Cooperating with FC and FCV verification (fleet) tests, and participating in actual planning and execution.
  - Cooperate in executing organizations by sending committee members.
  - Submit base plan for the verification tests.
  - Propose framework for the next phase verification tests after 2006.
- Cooperating with international standardization activities.
  - Participation in ICE/TC105, ISO/TC197 and ISO/TC22/SC21.
  - Coordinating the organizations (JEVA, ENAA and JEMA) acting as mirror committees to these standardization bodies within Japan.
- Investigating well-to-wheel energy efficiencies of related fuel chains.

After five years of activity, the FCCJ finished its first term in March 2006 and decided to continue further FC promotion activities for another five years as the second phase. The group reviewed past activities and identified remaining R&D themes and further activities to be stressed.

## Governmental activities

Along with the promotion of activities on the industry side, the government has also promoted the importance of RD&D in FC technologies to politicians. The prime minister of Japan showed deep interest and support for such activities. Responding to the strong initiative by the prime minister, the Fuel Cell Project Team of Senior Vice Ministers was formed in May 2002, consisting of three vice ministers from METI, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and the Ministry of Environment (MOE). The project team recommended the following expansion measures:

- basic scientific R&D
- demonstration
- public acceptance
- regulations and standards
- incentives for introduction.

The ministries responsible tried to respond to these recommendations, cooperating with industry as described above. Most of the tasks were finished by, or being continued at, the end of the 2005 financial year.

Among these tasks, review and revision of standards and regulations were regarded as the most urgent. A director-level task force from six ministries was formed in May 2002, and in October it released a roadmap for reviewing 28 regulations by 2005. It pointed out typical concerns and identified government agencies in charge (abbreviations are spelled out in the list of acronyms at the front of this volume), which are summarized as follows.

- High-pressure gas storage (METI/NISA/ISD)
  - gaseous hydrogen (GH) and liquid hydrogen (LH) tanks for vehicles and refuelling stations
  - valves and regulators for these applications.
- Vehicle certification processes (MLIT/RTB)
  - vehicle certification for safety, emissions and fuel economy.
- Restricted passage and protection of tunnels (MLIT/RB).
- H<sub>2</sub> storage capacity in residential areas (MLIT/HB).
- Fire hazards/protective measures at refuelling stations and parking garages (FDMA).
- Safe use of small stationary units at residences (FDMA).
- Safe connection with power grids (METI/NISA/EPSP).

Industry was also made responsible for providing technical data for “technical validation for government review”, and the corresponding FCCJ WG fully cooperated with this request. As a result, three areas and their responsible organizations were identified and allocated to solve those concerns.

- New technical standards for tanks used at above 35 MPa (JARI, JAMA, etc.).
- New technical standards for hydrogen refuelling stations (PEC, PAJ, JGA, etc.).
- New technical standards for safe installation and operation of small powered FC unit(s) at residential houses (JIA, JEMA, JGA, etc.).

Subsequently, the government established the following work scheme and review schedule.

- NEDO five-year project – Safe Production and Utilization of Hydrogen FY2003: ¥4.55 billion (US\$39 million)

- safety requirements on production, storage, transport and supply systems for vehicles and infrastructures (GH and LH)
- long-term effects of hydrogen on materials
- development of new technologies which make the use of hydrogen safer and more effective.
- Technical data derived from the above project were compiled in 2003 in time for the review process by government agencies in 2004.
- Some other agencies established their own projects outside NEDO.

Apart from codes and regulations within Japan, participation in international standardization related to hydrogen and FCV safety and quality/performance was also regarded as important to ensure international consistency in future technology. The FCCJ has coordinated with the JEVA, ENAA and JEMA, which are acting as member bodies of the International Electrotechnical Commission (IEC)/ISO standardization activities (fig. 2.7). This coordination is considered especially necessary to maintain the consistency of Japanese technology among the different ISO technical committees.

As for RD&D activities, METI, responding to requests from industry through the FCCJ, allocated an increased budget from 2002 to 2005; an exception among a general decrease in the total budget. The total budgets (in billions) for RD&D activities from 2002 were ¥18.5 (2002), ¥30.7 (2003), ¥32.9 (2004), ¥35.4 (2005) and ¥35.9 (2006), reflecting strong expectations and interest in FCV technology and commercialization.

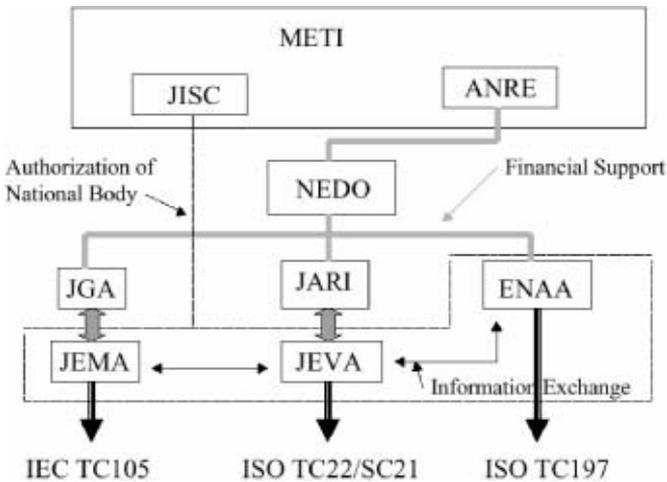


Figure 2.7 Scheme for international C&S activities

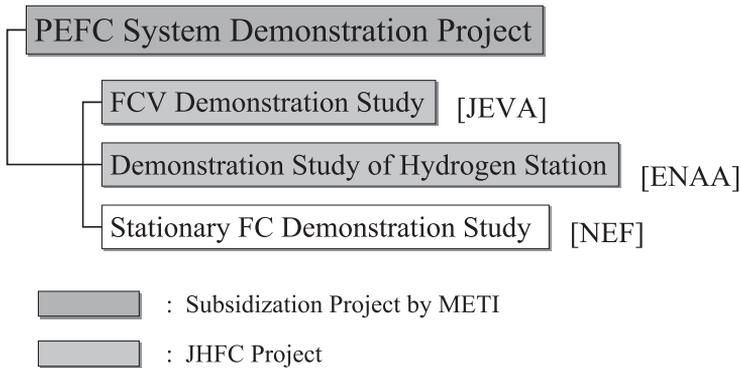


Figure 2.8 Scheme of PEFC system demonstration project

## FC and FCV demonstration activities

### *Outline and stationary FC demonstration*

As for FC and FCV demonstration, the government started verification tests for both stationary FC systems and FCVs with hydrogen refuelling stations from 2002. The METI PEFC Demonstration Project was allocated 10 per cent of the total budget for FC-related R&D, primarily to support installation of infrastructure and FC stack systems. The scheme of the project is shown in figure 2.8; the part related to FCV testing with hydrogen infrastructure was named the Japan Hydrogen and Fuel Cell project (JHFC). The JHFC was originally a three-year programme that started in 2002, but it was extended in 2005 and has only recently finished.

The general objectives of the JHFC project were to:

- prove validity and soundness of the PEMFC technologies selected
- evaluate total energy efficiency and fuel versatility
- acquire data for codes, standards and regulations
- identify issues in real-use conditions and in operation
- increase public awareness of FC technologies.

Although stationary FC co-generation systems will come into the market prior to FCVs due to higher cost allowance, there are severer requirements for durability and more complex reformer systems, as well as competition with alternative co-generation systems. In spite of these difficulties, gas companies eagerly promoted a demonstration programme, cooperating with several FC stack manufacturers. In the first three-year demonstration programme, 33 FC co-generation systems were installed

and evaluated in real-use conditions, and improved continuously by the manufacturers. The scope is summarized as:

- 1 kW FC unit for residential use
- 5 kW FC unit for business use
- sites spread all over Japan, including Hokkaido and Kyushu Island
- all units integrated into existing power grids without reverse flow
- unit operating information linked to central data-processing centre.

Among the 33 systems, two units were operated on pure hydrogen and naturally showed better performance at sites. All others have reformers, operating on various fuels. It was interesting that within two years overall FC system efficiency was improved by 15 per cent on average, and utilization of electricity and hot water was also improved by a similar level. The results showed that even with rather low heat demand in the Japanese climate, the FC co-generation system could reduce resource consumption and CO<sub>2</sub> emissions compared with conventional alternative systems. Durability has also much improved. After this experience, the government started a large-scale stationary fuel-cell demonstration project to supply subsidies for FC system purchases from 2005. In this project, within only one year more than 500 units had been installed, and it seems the diffusion phase of this technology has just started in this area.

### *JHFC FCV demonstration project*

The JHFC project, the FCV and hydrogen infrastructure part of the programme, has drawn more public attention due to the popularity and expectation of FCVs and hydrogen infrastructures. The goals of the project were to:

- show the energy-saving effect (thus CO<sub>2</sub> reduction and energy efficiency) of FCVs and hydrogen stations
- show how FCVs and hydrogen stations have a beneficial effect on the environment
- acquire useful data to develop codes, standards, regulations and laws for the safety and other issues of FCVs and hydrogen stations
- raise public awareness regarding FCVs and hydrogen stations
- clarify issues to be solved to promote the widespread use of FCVs and hydrogen stations.

The major features of the project were:

- extensive FCV demonstration study in Japan
- concurrent operational study of hydrogen stations with different types of fuels and different reforming methods
- METI subsidy for garages and hydrogen stations
- project management by a non-profit public association, acquiring test results from participants.

2002~05 FY			2003 ~ 05 FY
<b>Toyota</b>	<b>Nissan</b>	<b>Honda</b>	<b>Mitsubishi</b>
			
<b>Toyota FC</b>	<b>UTC FC</b>	<b>Honda FC &amp; Ballard FC</b>	<b>Ballard FC</b>
<b>CH 35MPa</b>	<b>CH 35MPa</b>	<b>CH 35MPa</b>	<b>CH 35MPa</b>
<b>Daimler CX</b>	<b>General Motors</b>	<b>Toyota/Hino</b>	<b>Suzuki</b>
			
<b>Ballard FC</b>	<b>GM FC</b>	<b>Toyota FC</b>	<b>GM FC</b>
<b>CH 35MPa</b>	<b>LH</b>	<b>CH 35MPa</b>	<b>CH 35MPa</b>

Figure 2.9 Car makers and FCVs participating in JHFC

Six car makers participated from the initial year, and two others and one bus manufacturer joined after 2003, as shown in figure 2.9. They all supplied test FCVs to the project, which are used to verify fuel economy regularly on assigned routes, and sometimes exhibited for demonstration events. The Japan Automotive Research Institute (JARI) organized a working group of car makers to plan and execute vehicle tests, data analysis and vehicle performance evaluation. In addition one bus was operated as a city bus on a normal service line in Tokyo for 15 months, and eight buses were operated daily during the Aichi Expo to connect two sites for six months in 2005. These demonstrations very effectively showed the new technology to the public.

From the initial year, 2002, several oil and fuel retail companies operated hydrogen refuelling stations: Cosmo Oil (gasoline reforming), Nippon Oil (naphtha reforming), Showa Shell Sekiyu and Iwatani International (LH storage), Japan Air Gases (methanol reforming), Nippon Sanso and Tokyo Gas (LPG reforming) and Nippon Steel Corporation (LH production from COG). Kurita, Shinanen and Ito-Chu Ene (alkaline electrolysis), Idemitsu (kerosene reforming), Pubcock Hitachi (city gas reforming) and Tsurumi Soda (off-site H<sub>2</sub> storage) joined in 2003. Further, in 2005 two hydrogen stations were built by Toho Gas and Nippon Steel, which participated in the JHFC for bus operation at the Aichi Expo. One of these stations reforms hydrogen from city gas on site. The other is operated by a steel company, providing pure hydrogen separated

from COG (coke-oven gas) by PSA (pressure swing adsorption) at the steel plant, and carried by compressed hydrogen containers. These two systems were selected as the final station constructions in the JHFC as potentially efficient hydrogen-producing paths under Japanese conditions. As shown in figure 2.10, 10 hydrogen refuelling stations were built around the western part of Tokyo, intentionally focusing on small areas considered important in future commercialization.

Major specifications of supplied H<sub>2</sub> are:

- gas composition: H<sub>2</sub> > 99.99 per cent, CO < 1 ppm, O<sub>2</sub> < 2 ppm, CO<sub>2</sub> < 1 ppm, N<sub>2</sub> < 50 ppm, HC < 1 ppm
- supply pressure: high pressure 35 MPa; low pressure 25 MPa
- capacity: Type A – 5 cars in series (35 Nm<sup>3</sup> × 5 = 175 Nm<sup>3</sup>); Type B – 5 cars a day (35 Nm<sup>3</sup>/vehicle); Type C – 1 bus a day (175 Nm<sup>3</sup>/bus).

According to the objectives of the JHFC, the following data were collected from test cars throughout the project.

- Fuel economy – test conditions, drive pattern (speed, range etc.) and refuelling (station, quantity, time, etc.) records.
- Driving performance – reliability, acceleration, starting ability and response and maintenance.
- Environmental impact – noise, H<sub>2</sub> leakage and emissions.
- Reference for standards – H<sub>2</sub> safety issues.

These data were carefully investigated and evaluated, not only by individual car makers but within JHFC working groups. The results were shared by all participants, as the vehicles were still in the test and development phase and common problems and responses may be helpful for further R&D.

In the test period, total run distance of the test passenger cars and hydrogen consumption reached over 84,000 km and 1,390 kg respectively. For the bus operation at the Aichi Expo site, more than 1 million people experienced the high performance of FC buses, and the total run distance was over 127,000 km, consuming 11.4 tonnes of hydrogen.

At the end of 2005 data were summarized and evaluation results were openly reported to the public. During the period, energy consumptions of other types of vehicles, i.e. internal-combustion-engine vehicles (ICEVs) and hybrid electric vehicles (HEVs), with equivalent grades were also evaluated for comparison. As the energy consumption of a vehicle depends heavily on drive cycle, fuel economies for every five minutes were evaluated for all running tests, assuming that average speeds represent primary driving conditions. Figure 2.11 shows comparison results, which verify that the fuel economy of FCVs is better than that of equivalent conventional vehicles for most speed ranges. Impacts of air conditioning and performance gaps among vehicles also clarified the technological potential of FCVs. It was interesting that there were significant improvements in average fuel economy in the last two years of evaluation even

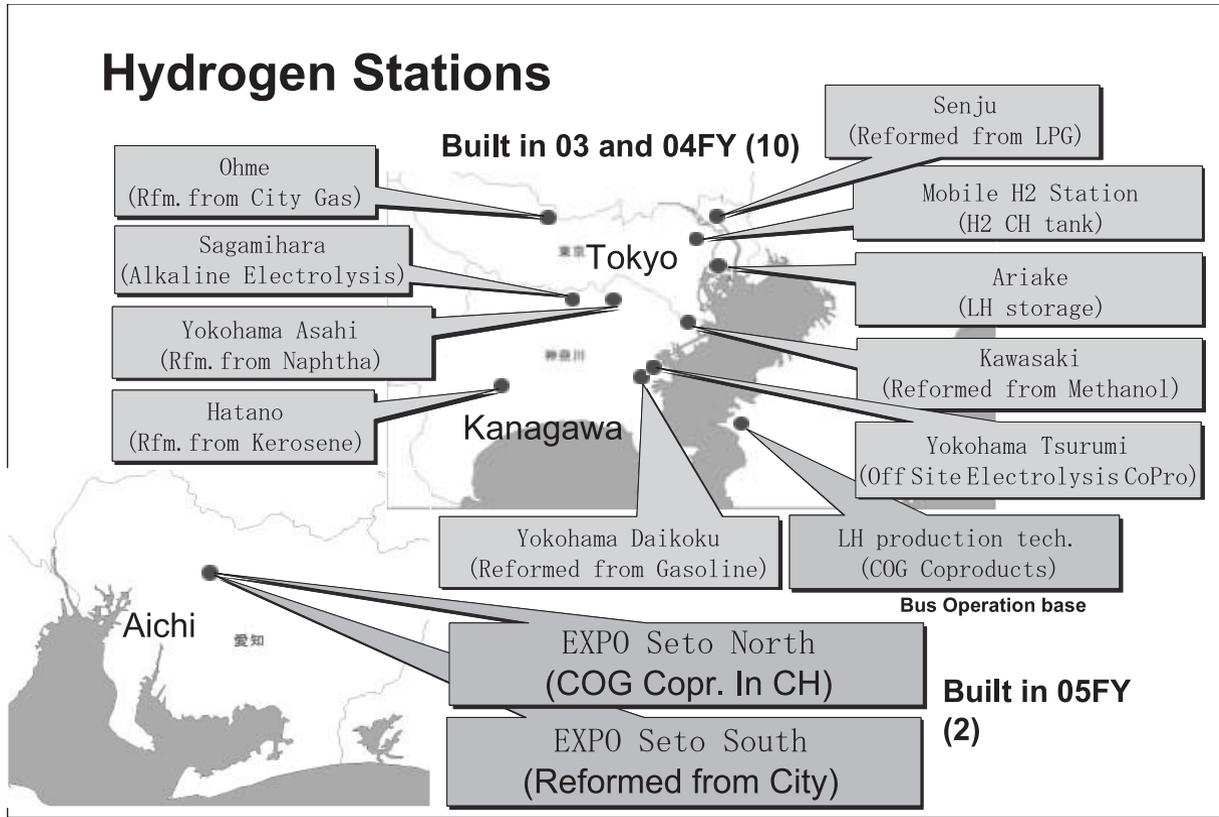
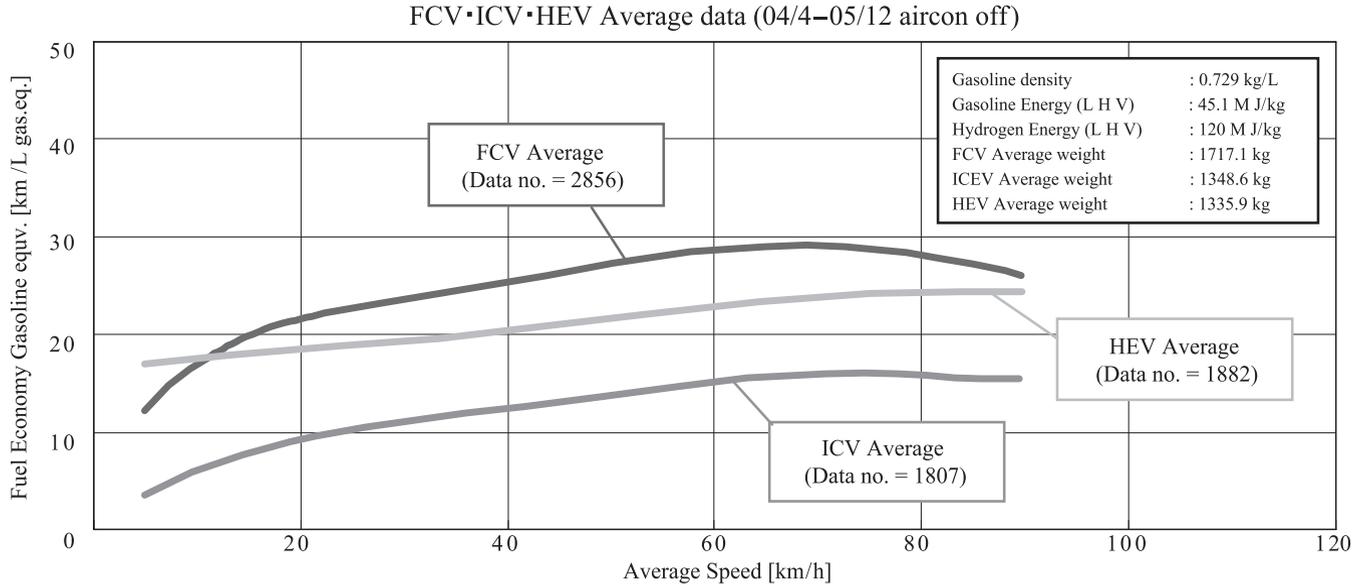


Figure 2.10 JHFC hydrogen stations



FCV : FCHV, X-TRAIL FCV, FCX, HydroGen3, F-Cell, Mitsubishi FCV, Wagon R-FCV  
 (Most of them are hybrid type)  
 ICV : Cluger, X-TRAIL, CR-V, Astra, Class A, Grandis, Wagon R  
 HEV : Prius, Old Prius, Estima Hybrid, Tino Hybrid, Insight

Figure 2.11 Fuel economy of various types of vehicles for the same drive conditions

though the top-class performance remained almost the same. This suggests that even in one year the technology gap was reduced significantly, and that vehicle system technology may achieve levels acceptable to the market. However, reliability, durability and cost are not mentioned here. This kind of quantitative evaluation for the most advanced FC technology is quite rare, and will contribute to further cooperation in R&D among stakeholders. However, this analysis also showed that the technology is still in the pre-market phase, and cooperation is required more than competition to realize acceptable FCVs.

### *Well-to-wheel analysis*

The actual efficiency of hydrogen reforming from various hydrocarbon fuels is also evaluated in the JHFC project, although some stations cannot reach the target efficiency due to insufficient demand from FCVs. For technology evaluation, potential performance of existing technology was also studied. These evaluation results were also reported openly in March 2006. Overall well-to-wheel (WtW) energy resource consumption and CO<sub>2</sub> emissions for various alternative vehicles were studied in an overall efficiency study group organized in the JHFC in order to give unbiased and transparent information to judge the current status, significance and/or effects of the technology. The mandate of the study was to evaluate WtW energy efficiency and CO<sub>2</sub> emissions for various fuel paths and drive trains, focusing on hydrogen FCVs, under Japanese conditions, especially those of well-to-tank (WtT), reflecting data and knowledge obtained through the JHFC project.

It was also intended to provide a reliable and authorized database for such WtW analysis in Japan, bringing together all available expertise and knowledge. Members of the study group came from universities, research institutes, related industry associations (cars, gas, electric power, oil), the FCCJ, the World Business Council for Sustainable Development (WBCSD) and the JHFC, as well as researchers experienced in life-cycle assessment (LCA), so that the results could act as firm and acceptable standards for Japanese WtW research. Over three years, available reference data, especially those for WtT paths, were collected from published materials or actual study reports open to the public, and evaluated. The resultant data were summarized in the JHFC database. And together with the TtW (tank-to-wheel) investigation and test data, a final WtW analysis was made in March 2006. The study group hosted a workshop where results were discussed in detail with experts from the United States and the European Union.

Figure 2.12 shows an example of WtW energy consumption and CO<sub>2</sub> emissions for FCVs (with various fuel paths) and conventional ICEVs for a Japanese drive cycle by a compact passenger car. All WtT process

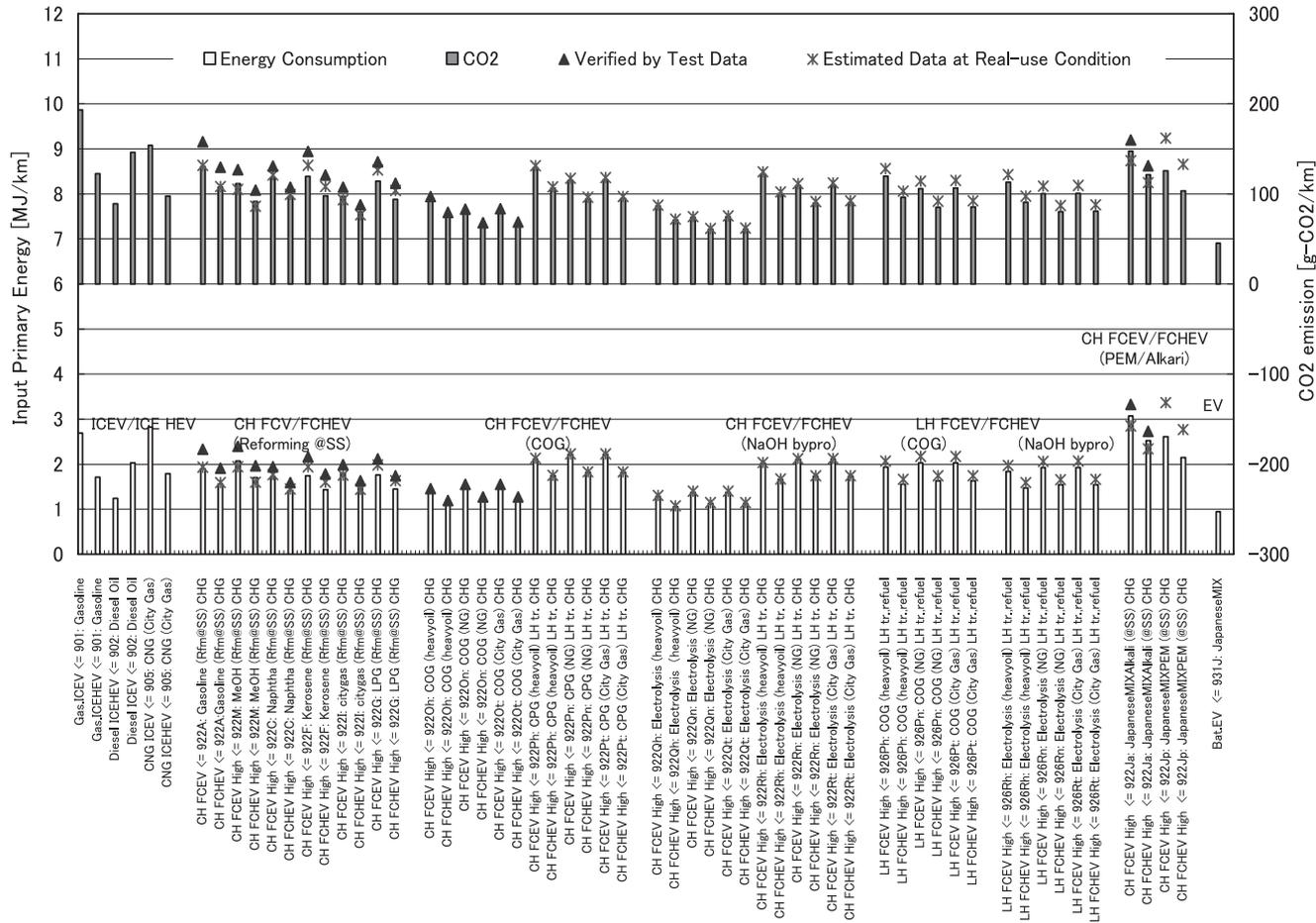


Figure 2.12 An example of results of well-to-wheel analysis

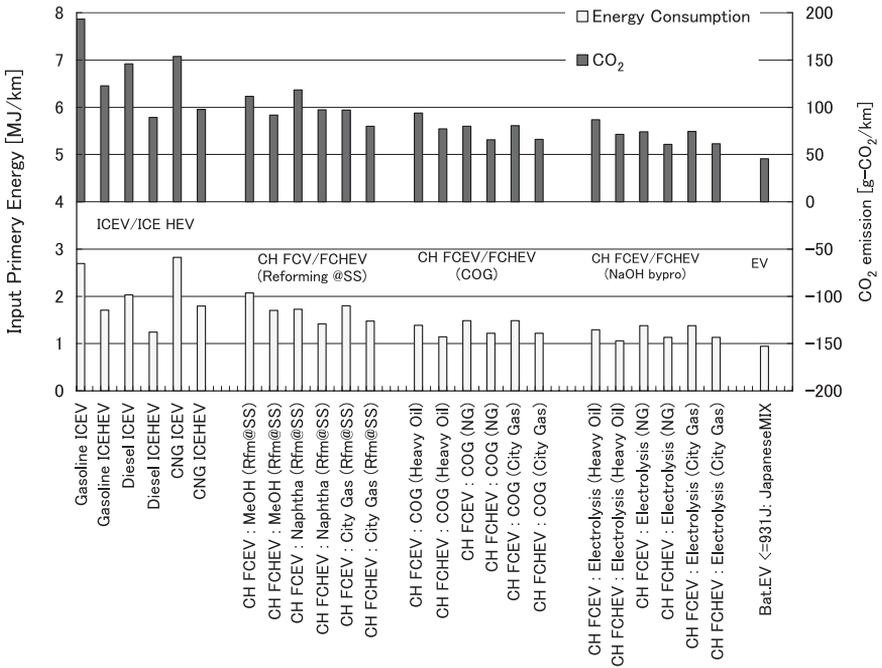


Figure 2.13 Comparison of ICEVs and FCVs by well-to-wheel analysis

data are based on the reference data, and compared with verified test data in the analysis. Triangles and crosses in the graph show corresponding results using actual and expected data by the current technology performance. Although there are gaps in some fuel paths, verified data generally match well, and this analysis was confirmed by the JHFC data.

Figure 2.13 shows examples of WtW paths for energy efficiency. From the figure, it can be concluded that even using hydrocarbon fossil fuels to produce hydrogen, some FCVs will be more efficient than any other alternative vehicles existing or under consideration, including diesel hybrid vehicles. However, in this figure target FC stack efficiency is assumed as 60 per cent – a 10-point gap from the current status. This means that further efficiency improvements are required to justify the technology, but the results also show that the target value is reasonable.

### Remaining issues and further R&D plans

With these intensive activities to verify and promote FC technology over the past five years, it has been widely recognized that fuel cells are still in

the developing phase and may need more time to be competitive in the market. However, it is again verified that this technology can be a very promising long-term option for CO<sub>2</sub> reduction and energy conservation for both the transportation sector and household energy use. It is also confirmed that the most critical issues to be pursued for the moment are hydrogen storage and durability and cost reductions in FC stacks. As for hydrogen infrastructure, i.e. hydrogen production and distribution, there are many problems to be solved, but compared with the major issues in FC stacks the technical hurdles in this area are comparatively low, except for cost reductions and hydrogen storage materials.

With those considerations, the government asked industry to pay attention to basic research, “back to the basics”, with a focus on the basic mechanisms in the deterioration of the membrane or catalyst within FC stacks during operation. METI established two national laboratories, the Polymer Electrolyte Fuel Cell Cutting-Edge Research Center (known as FC<sup>3</sup>) and the Laboratory for Hydrogen Material R&D; METI intends to maintain the present size of its RD&D budget for FC-related technologies, and some of this will be put towards these two national laboratories through NEDO. The FCCJ has also recognized basic issues, and organized a special committee in 2005 to identify basic R&D areas to be solved over the next five years. The committee established several working groups with expertise from member companies, and each group discussed every issue in detail and clarified quantitative targets required for further R&D or commercialization. Issues included:

- polymer electrolytes, MEA (membrane electrode assembly) and catalysts, and specification for automotive use
- on-board hydrogen storage, practical targets for specifications and a roadmap to attain them
- on-board materials for hydrogen treatment: brittle failure mechanisms, R&D for materials and durable and inexpensive equipment regarding hydrogen tanks and piping etc.
- R&D for polymer electrolytes and MEA for stationary-use FCs
- cost reductions and reliability improvements for FC cogeneration systems
- hydrogen production, distribution, reliability, safety and cost reductions.

Results of these activities reflect industry’s needs for further R&D for commercialization, and in some cases quantitative targets for commercialization have been identified.

As for demonstration projects, a further plan called JHFC2 kicked off in May 2006. Efforts will build on the stations created in the past JHFC, but in order to expand public acceptance in areas outside Tokyo it is now planned to build new hydrogen stations in the Nagoya and Osaka areas.

City buses will operate around Aichi international airport, and passenger FCV fleet tests under severer use conditions are now being planned to clarify deterioration qualities under real operation. Some other niche areas for FC utilization, like bicycles and wheelchairs, will be promoted. For outreach activities the importance of educating opinion leaders and decisionmakers by providing unbiased information is strongly recognized. The significance and necessity of long-term R&D and appropriate expectations for outcomes are also recognized.

Finally, the Council of Science and Technology, under the Cabinet Office, issued the Third Science and Technology Basic Plan in March 2006. Within the plan, the council identified essential research and development issues for eight prioritized areas, including energy, and further indicated strategically focused science and technology areas which should be strengthened in the next five years. In the energy area, FC technology, FCVs and stationary-use FC systems are all assigned as essential research areas; and FC stacks, hydrogen distribution/storage and FCVs are identified under strategically focused science and technology. Related ministries, such as METI, the MLIT and MOE, will promote further RD&D activities in due time.

FCVs still face many significant challenges, whereas stationary-use systems are now entering commercialization. Indeed, many hydrogen infrastructure technologies already exist, and the promotion of hydrogen networks is becoming increasingly popular around the world. However, the lack of FCV supply to use such infrastructures is a major hurdle. Some attempts are being made to utilize excess hydrogen for stationary use through small-scale hydrogen networks. Japanese fleet tests, while significant, are still restricted to narrow areas and support a limited number of vehicles. The balance and timing for FCV commercialization should be carefully considered for future promotion and planning.

## Note

1. For details on the progress made in cost reductions in 2005, see chapter 3 in this volume.

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## 3

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## The US Hydrogen Fuel Initiative

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*Steven G. Chalk and James F. Miller*

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This chapter reviews the progress made in research and development under the US Hydrogen Fuel Initiative. Technical progress is measured against a set of quantitative objectives, and a number of the targets have been met earlier than anticipated. However, hydrogen cost and availability and fuel-cell durability and cost are formidable challenges still to be solved. While further research remains important, attention is also now being given to manufacturability and market transformation activities in anticipation of commercialization.

In his 2003 State of the Union address, President Bush announced the \$1.2 billion Hydrogen Fuel Initiative to reverse America's growing dependence on foreign oil (shown in fig. 3.1) and improve the environment by developing the technology needed for commercially viable hydrogen-powered fuel cells. Through partnerships with the private sector, the president's Hydrogen Fuel Initiative seeks to develop the hydrogen and fuel-cell technologies needed to make it practical and cost-effective for Americans to choose hydrogen-powered fuel-cell vehicles by 2020. In support of President Bush's initiative, the Department of Energy (DOE) is leading a comprehensive and focused research and development programme to overcome the technical and economic barriers to a hydrogen economy.

Because hydrogen can be produced from diverse domestic resources, the initiative will dramatically improve America's energy security by significantly reducing the need for imported oil. At the same time, it is a key component of the president's clean air and climate change strategies.

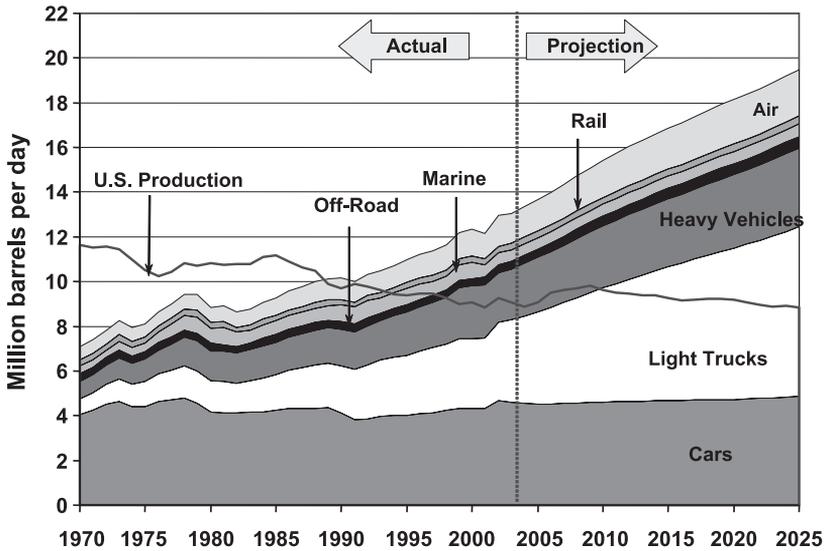


Figure 3.1 US domestic oil production and petroleum use in transportation

Hydrogen-powered fuel cells decouple carbon from power generation and emit only water vapour (i.e. zero criteria pollutants). The DOE has planned and is executing a balanced research portfolio for developing fossil, nuclear and renewable-based hydrogen production and delivery technologies. Hydrogen from coal will be produced directly by gasification – not coal-based electricity. For hydrogen from coal to be viable, research in carbon capture and sequestration technologies must also be successful. The ultimate goal is a hydrogen economy based on carbon-neutral fossil, nuclear and renewable energy resources.

## US Hydrogen Program

The DOE Hydrogen Program, which includes the Offices of Energy Efficiency and Renewable Energy (OEERE), Fossil Energy (OFE), Nuclear Energy, Science and Technology (ONE) and Science (OSC), emphasizes research, development and validation of fuel cells and hydrogen production, delivery and storage technologies for transportation, distributed generation and portable power applications. The programme seeks to enable an industry commercialization decision on fuel-cell vehicles and fuelling infrastructure by 2015.

The OEERE coordinates the programme and conducts research and development on fuel cells, hydrogen production, delivery, storage, analysis, infrastructure and safety, codes and standards, with an emphasis on production of hydrogen from distributed natural gas and from renewable resources. The OFE is focused on low-cost, novel and advanced coal-based hydrogen production and delivery technologies. The ONE's emphasis is the commercial-scale production of hydrogen using heat from a nuclear energy system. The OSC fosters revolutionary advances in hydrogen production, delivery, storage and conversion technologies to increase fundamental understanding of hydrogen's interactions with materials. Recently, 70 new projects were selected by the OSC, at \$64 million over three years, to address novel materials for hydrogen storage, membranes for hydrogen separation and purification, designs of catalysts at the nano scale, solar hydrogen production and bio-inspired materials and processes. In addition, the Department of Transportation (DOT) works with the DOE in conducting safety analyses and testing of hydrogen-related processes and equipment, as well as implementing a comprehensive safety testing and evaluation programme for hydrogen fuel cells.

## Hydrogen production

Four DOE offices are engaged in research on hydrogen production technologies. The OEERE is developing technologies for producing hydrogen in a distributed manner from natural gas and liquid renewable fuels and by electrolysis of water, and is developing centralized renewable production options that include water electrolysis using renewable power (e.g. wind, solar, hydroelectric, geothermal), biomass gasification, photo-electrochemical and biological processes and high-temperature solar thermochemical cycles. The OFE is focused on advancing the technologies needed to produce hydrogen from coal-derived synthesis gas, including co-production of hydrogen and electricity as well as carbon sequestration. The ONE is developing commercial-scale production of hydrogen using heat from a nuclear energy source. The OSC's basic research programme is emphasizing fundamental understandings of bio-inspired materials and processes, photo-induced water splitting, catalysis, membranes and gas separation.

In the transition to the hydrogen economy, hydrogen can be produced in a "distributed" fashion at the refuelling station by reforming natural gas and renewable fuels like ethanol utilizing existing delivery infrastructure to meet initial lower volume needs with the least capital investment. Fuel reformers would not require a substantial hydrogen transport and

delivery infrastructure. Research and development is under way to lower the capital, operating and maintenance costs and improve the efficiency of distributed hydrogen production technologies. This approach has the advantage of eliminating the need for new hydrogen delivery infrastructure investment while vehicle demand is low. A fuel-cell vehicle running on hydrogen produced from natural gas would emit 25 per cent less net carbon emissions than a gasoline hybrid electric vehicle and 50 per cent less than conventional internal-combustion-engine vehicles on a well-to-wheel basis. However, natural gas is not a long-term strategy because of concerns about limited supply and the demands of other sectors. As vehicle market penetration expands, it justifies greater industry investment in large-scale, carbon-neutral hydrogen production and delivery infrastructure based on coal, nuclear and renewable resources.

### *Goal, objectives and key challenges*

The programme goal is to develop low-cost, highly efficient hydrogen production technologies from diverse domestic sources, including fossil, nuclear and renewable sources, as shown in figure 3.2. Specific objectives are listed below.

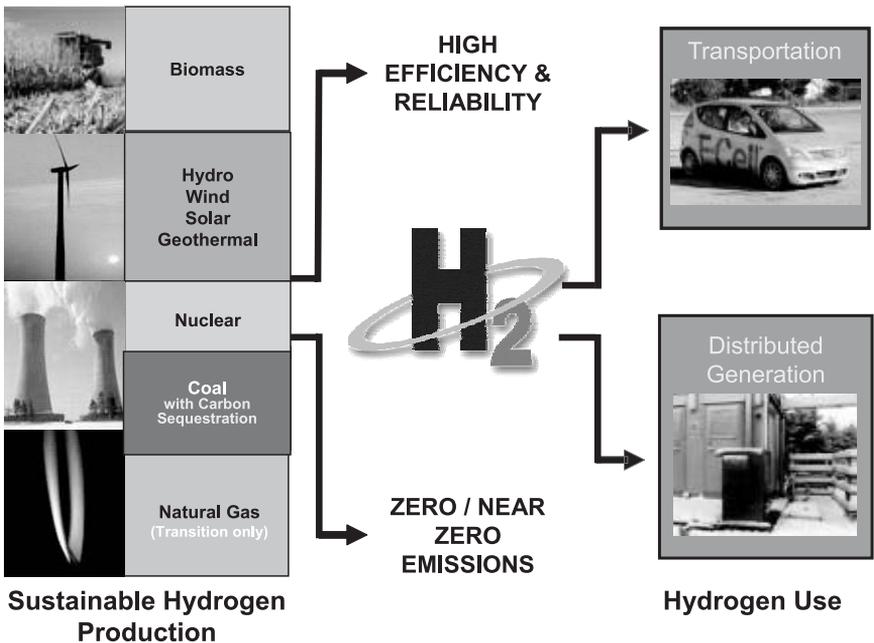


Figure 3.2 Hydrogen production pathways in the US Hydrogen Program

- By 2010 reduce the cost of distributed production of hydrogen from natural gas to \$2.50/gge (per gallon gasoline equivalent) (delivered, untaxed) at the pump.
- By 2015 reduce the cost of distributed hydrogen production from biomass-derived renewable liquids to \$2.50/gge (delivered, untaxed) at the pump.
- By 2010 verify distributed grid-connected water electrolysis at a projected delivered hydrogen cost of \$2.85/gge.
- By 2015 verify renewable central hydrogen production at a projected cost of \$2.75/gge delivered.
- By 2015 reduce the cost of hydrogen produced from biomass to \$1.60/gge at the plant gate (\$2.60/gge delivered) by developing reforming technologies for gasification processes.
- Develop advanced renewable photoelectrochemical and biological hydrogen generation technologies. By 2015 verify the feasibility of these technologies to be competitive in the long term.
- By 2015 develop high-temperature thermochemical cycles driven by concentrated solar power processes to produce hydrogen with a projected cost of \$3.00/gge at the plant gate (\$4.00/gge delivered).
- By 2015 have ready to operate a zero-emissions, high-efficiency co-production power plant that will produce hydrogen from coal along with electricity.
- Demonstrate the commercial-scale, economically feasible production of hydrogen using nuclear energy by 2017.

In 2005 the hydrogen cost target was revised to a range of \$2.00–3.00/gge of H<sub>2</sub> at the pump in 2015, as shown in figure 3.3. This target is inde-

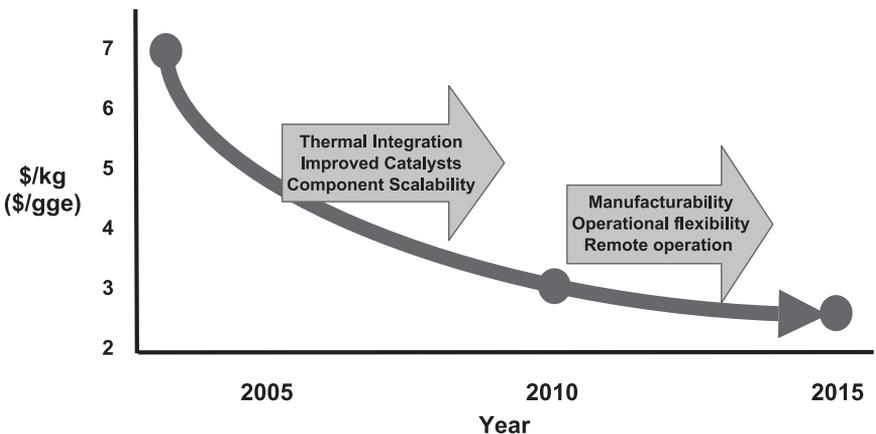


Figure 3.3 Hydrogen production cost targets

pendent of the pathway used to produce hydrogen, and accounts for the energy efficiency of the gasoline hybrid vehicle and the fuel-cell vehicle on a cost-per-mile basis. The target provides a yardstick against which the commercialization potential of different hydrogen production technologies can be measured.

### *Recent progress and technology status*

Hydrogen production using reforming of natural gas is approaching its target of \$3.00/gge for hydrogen at the pump (5,000 psi). Recent progress indicates a projected cost of \$3.60/gge for hydrogen produced from natural gas, delivered and untaxed, while co-producing electricity at \$0.08/kWh. This is down from approximately \$5.00/gge prior to 2003. Other production and delivery technologies are in various stages of development.

In terms of specific recent accomplishments, the programme has achieved the following.

- Designed two distributed natural-gas-to-hydrogen production and dispensing systems expected to produce 5,000 psi hydrogen at a cost of \$3.00/gge, based on a fourfold reduction in pressure swing adsorber cost, improved fuel processing via steam methane reforming and development of an efficient and compact autothermal cyclic reformer.
- Achieved 2,000 psi hydrogen production in a planar electrolysis stack.
- Developed new electrolysis system designs with 40–50 per cent part count reduction.
- Developed a new design for electrolysis systems with potential for achieving a hydrogen production cost of \$2.85/gge by 2010.
- Evaluated alkaline and proton-exchange-membrane electrolysis technologies for high-pressure operation.
- Completed the criteria-based screening of over 200 potential solar-driven high-temperature thermochemical cycles, down-selected to four groups of cycles (volatile metal, metal oxide, sulphate and sulphuric acid) and initiated research on these cycles. The zinc oxide cycle high-temperature ( $\sim 1,800^\circ\text{C}$ ) reduction step to zinc metal was demonstrated in the laboratory.
- Conceptual design documents were completed for pilot-scale thermochemical cycle experiments (200 kW high-temperature electrolyser experiment and 500 kW sulphur-iodine thermochemical process experiment).
- Initiated an International Partnership for the Hydrogen Economy global project on solar-driven high-temperature thermochemical cycles for hydrogen production, with solar energy research groups from Switzerland, Germany, France, Israel, Spain and the United States.

- Durability of 760 hours (up from 100 hours in 2003) was demonstrated with a new gallium phosphide nitride material producing hydrogen via photoelectrochemical technology.
- Oxygen tolerance in photolytic biological hydrogen production from water was increased by 40–50 per cent.

### *Future plans*

The programme will continue to focus on distributed natural gas and renewable liquid reforming, distributed electrolysis, biological and photoelectrochemical processes, central biomass reforming, solar high-temperature thermochemical cycles and hydrogen separation technologies. In addition, a hydrogen utility working group will be established to increase collaboration with electric utilities on electrolysis technology development. High-temperature electrolysis systems will be evaluated for higher-efficiency operation. The sulphur-iodine cycle chemical component reaction sections will be operated individually prior to integrated laboratory-scale system operation in 2008. The number of solar-driven high-temperature thermochemical cycles under consideration will be reduced to four or fewer cycles for development. A database on photoelectrochemical materials will be developed to allow material data sharing among researchers. And standardized testing protocols for photoelectrochemical materials will be established for validating efficiencies and permitting functional comparisons between materials.

## Hydrogen delivery

Hydrogen must be transported from point of production to point of use. It must also be compressed, stored and dispensed at refuelling stations or stationary power facilities. Due to its relatively low volumetric energy density, transportation, storage and final delivery to the point of use can result in significant cost and energy inefficiencies. The programme is focused on developing technology to reduce the cost and increase the energy efficiency of hydrogen delivery. Research efforts are focused on delivery infrastructure analysis, lower-cost pipelines, lower-cost off-board storage at refuelling stations, liquid carriers, lower-cost and more energy-efficient liquefaction and more durable and reliable compression technology.

### *Goal, objectives and key challenges*

The programme goal is to develop hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy

carrier for transportation and stationary power. Specific objectives are listed below.

- By 2007 define criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the transition and long-term use of hydrogen for transportation and stationary power.
- By 2010 reduce the cost of hydrogen transport from central and semi-central production facilities to the gate of refuelling stations and other end users to <\$0.90/gge of hydrogen.
- By 2010 reduce the cost of compression, storage and dispensing at refuelling stations and stationary power facilities to <\$0.80/gge of hydrogen (independent of transport).
- By 2015 reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <\$1.00/gge of hydrogen in total.

In order for hydrogen to become a major energy carrier, the total delivery cost must be substantially reduced. If hydrogen was a major energy carrier transported in large volumes and there was a pipeline infrastructure of the nature of the current natural gas infrastructure, the total cost of hydrogen delivery could be in the order of \$2.00/gge with existing technology. The long-term goal for delivery is \$1.00/gge of hydrogen. Therefore, significant technology development is needed.

- *Pipelines:* resolve hydrogen embrittlement concerns with steel pipelines, reduce capital costs by developing new steel compositions and/or welding and installation techniques, and develop composite pipelines with reduced capital costs.
- *Compression:* develop more reliable and durable hydrogen compression technology for pipeline transmission and refuelling stations.
- *Storage:* develop lower capital cost off-board storage vessel technology; confirm the technical feasibility and adequate availability of hydrogen geologic storage.
- *Liquefaction:* dramatically reduce the capital cost and increase the energy efficiency of hydrogen liquefaction.
- *Carriers:* determine if a novel solid or liquid carrier might be suitable for hydrogen transport or off-board storage.

### *Recent progress and status*

Current costs for the transport of hydrogen, with the exception of that transported through the very limited number of hydrogen pipelines, are \$2.00–9.00/gge of hydrogen. This is based on transport by gaseous tube trailers or cryogenic liquid trucks, and is very dependent on amounts and distances. Pipeline transport costs are significantly lower, but are also very dependent on distance and amounts. These transport costs do not include the delivery costs associated with compression, storage and

dispensing at the point of use. These additional costs could be as high as \$2.00–3.00/gge of hydrogen.

Specific recent activities and accomplishments include the following.

- Development of H<sub>2</sub>A delivery component and scenario modelling tools, which include the current costs of hydrogen delivery using pipelines, liquid trucks and gaseous trucks.
- Formation of a pipeline working group which cross-cuts all the pipeline research projects, enabling more efficient and effective pipeline research.
- Membership on the EC Naturalhy Project Strategic Advisory Committee, focused on the use of existing natural gas infrastructure for the co-transport of natural gas and hydrogen, thereby avoiding global duplication of research.

### *Future plans*

The programme will expand hydrogen delivery infrastructure analysis to include carrier technology approaches, more comprehensive regional and other geographic-specific aspects and more in-depth transition analysis. It will also initiate additional research focused on compression, off-board storage, high-pressure tube trailers and liquefaction.

## Hydrogen storage

Hydrogen storage continues to be a key enabling technology for the advancement of hydrogen and fuel-cell power technologies in transportation, stationary power and portable power applications. Activities focus primarily on R&D of on-board hydrogen storage systems that will allow for a vehicular driving range of 300 miles or more. In addition, hydrogen storage systems are targeted for off-board applications such as hydrogen delivery and refuelling infrastructure, and interface technologies for the refuelling of hydrogen storage systems on vehicles.

The National Hydrogen Storage Project is organized as shown in figure 3.4. Three centres of excellence and 15 independent projects were initiated in 2005. The centres are a collaboration between multiple university, industry and federal laboratory partners, representing a concerted, multi-disciplinary effort to research and develop hydrogen storage materials. Planned funding totals \$150 million over five years. Independent testing and analysis of promising approaches are also under way.

The Hydrogen Storage Systems Analysis Working Group was formed in 2005 to coordinate systems analysis work across the storage subprogramme and aid in assessing technologies on a systematic basis in terms

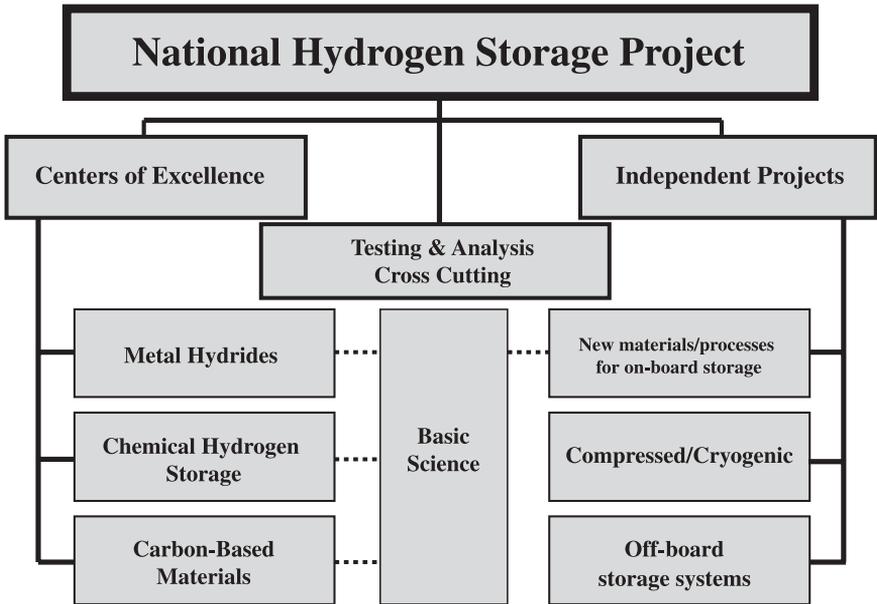


Figure 3.4 Organization of the US Department of Energy Hydrogen Storage Project

of life-cycle cost, performance, energy efficiency and environmental impact. The group meets semi-annually, with monthly interim progress meetings.

*Goal, objectives and key challenges*

Technical and cost targets are shown in table 3.1. On-board hydrogen storage approaches under investigation include advanced metal hydrides,

Table 3.1 Hydrogen storage technical and cost targets

	2010	2015
System gravimetric capacity (specific energy)	2.0 kWh/kg	3.0 kWh/kg
	7.2 MJ/kg	10.8 MJ/kg
	6 wt %	9 wt %
System volumetric capacity (energy density)	1.5 Wh/L	2.7 Wh/L
	5.4 MJ/L	9.7 MJ/L
	0.045 kg/L	0.081 kg/L
System cost	\$4/kWh	\$2/kWh
	\$133/kg H <sub>2</sub>	\$67/kg H <sub>2</sub>

carbon-based materials and other high-surface-area sorbents, chemical hydrogen storage, low-cost and conformable tanks, compressed/cryogenic hydrogen tanks and new materials or processes, such as clathrates and conducting polymers. Compressed/cryogenic tanks, metal hydrides, high-surface-area sorbents and carbon-based materials constitute on-board reversible hydrogen storage systems because hydrogen regeneration or uptake can take place on board the vehicle. For chemical hydrogen storage approaches as well as certain metal hydrides, hydrogen regeneration is not possible on board the vehicle; thus these systems must be regenerated off-board.

R&D for advanced metal hydrides is focusing on light element, advanced complex hydrides; destabilized binary hydrides; intermetallic hydrides; lithium amides; and other reversible hydrides. Chemical hydrides are focused on novel boron chemistry (boron hydrides, aminoboranes, polyborane anions) as well as advanced concepts for chemical hydrogen storage, regeneration chemistry and life-cycle analysis. Carbon-based materials are targeting absorbents such as hybrid carbon nanotubes, conducting polymers, metal organic frameworks and other novel carbon-based materials. In addition, novel materials such as clathrates and glass microspheres are being investigated.

### *Recent progress and status*

The current technical status, shown in figure 3.5, is based on estimates provided by developers and the R&D community. Because it is often difficult to estimate system-level weight and volume when research is still at the stage of materials development, the current status data will be revisited periodically. However, it is clear that none of the current systems meets the combined gravimetric, volumetric and system cost targets for either 2010 or 2015.

Significant progress was achieved in 2005 in metal hydrides, chemical hydrides, carbon materials and compressed-gas tanks. Specific recent accomplishments include the following.

- Metal hydrides.
  - Completed lab-scale experiments identifying alane ( $\text{AlH}_3$ , theoretical materials-based capacity of 10 wt per cent) as a promising candidate with potential to meet 2010 targets. Lowered the desorption temperature of the as-received  $\alpha$ - $\text{AlH}_3$ , which ranged from 175–200°C to 100–150°C (6–7 wt per cent hydrogen evolved) by mechanically milling the material with an LiH dopant (Brookhaven National Laboratory and Sandia National Laboratories).
  - Achieved 5.5 wt per cent reversible hydrogen storage through the development of a destabilized Mg-modified Li-imide material (San-

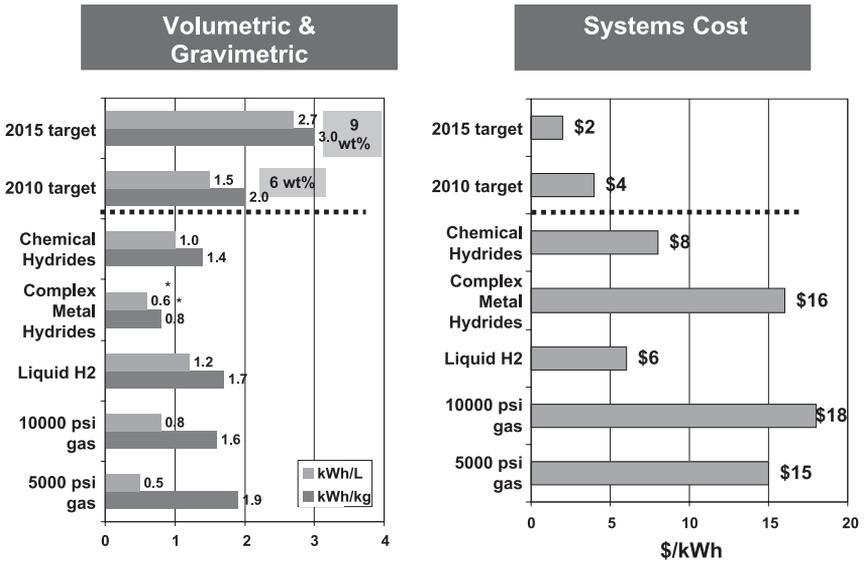


Figure 3.5 Current technical status of hydrogen storage technologies and targets

dia). Demonstrated over 100 cycles of use of this material and characterized loss of activity over the period due to a combination of material loss and material degradation.

- Developed and demonstrated  $\text{LiBH}_4/\text{Mg}(\text{X})$  as a class of promising high-capacity destabilized systems, with partial to complete reversibility demonstrated for  $\text{X} = \text{H}, \text{F}$  and  $\text{S}$  ( $\text{LiBH}_4/\text{MgH}_2 \sim 9$  wt per cent at  $350^\circ\text{C}$ ). However, these systems also display slow kinetics; future work will focus on enhanced reaction rates in nano-scale materials (HRL Laboratories).
- Chemical hydrogen storage.
  - Developed and demonstrated ethyl-carbazole-based and similar organic liquid carriers with hydrogen storage capacities of 5.0–6.9 wt per cent (Air Products & Chemicals).
  - Discovered non-metal, non-precious metal and general classes of transition metal catalysts for releasing hydrogen from ammonia-borane, which has a potential material hydrogen storage capacity of 19.6 wt per cent (Los Alamos National Laboratory, Pacific Northwest National Laboratory, University of Pennsylvania and University of Washington).
  - Discovered that ammonia-borane in inorganic scaffolds leads to increased kinetics of hydrogen release with no borazine formation;

showed  $\sim 6$  wt per cent hydrogen storage at low temperatures (Pacific Northwest National Laboratory).

- Demonstrated hydrogen release from a hetero-atom containing “organic hydride” (Los Alamos and University of Alabama).
- Demonstrated a coupled reaction with potential hydrogen storage capacity of  $>6$  wt per cent (Los Alamos).
- Carbon-based materials and sorbents.
  - Using theory, designed fullerene derivative/metal hybrids with the potential to store  $>8$  wt per cent at room temperature (National Renewable Energy Laboratory – NREL).
  - Optimized synthesis and purification processes to produce metal-doped single-walled nanotubes reproducibly, with 2–3 wt per cent and 2.9 wt per cent demonstrated at an independent test facility (NREL).
  - Developed polyaniline-based conducting polymers for hydrogen adsorption to test claims of  $\sim 6$  wt per cent materials-based hydrogen storage capacity (University of Pennsylvania).
  - Determined that the binding energy for hydrogen zinc oxide corner units in metal organic frameworks increases the overall sorption enthalpy from 4.1 kJ/mol to 6.1 kJ/mol by changing the organic linker (Cal Tech).
  - Incorporated boron into carbon materials, demonstrating greater than threefold improvement in hydrogen adsorbed at ambient temperature (from  $<0.2$  to 0.7 wt per cent) (Pennsylvania State University).
- Compressed and cryogenic tanks.
  - Completed preliminary optimization of low-cost 10,000 psi tanks to achieve 1.3 kWh/kg specific energy. Identified approaches with potential to lower cost from \$18/kWh to \$10/kWh.
  - Completed design of cryo-compressed tank system with potential to meet 1.2 kWh/L.
- Testing and analysis.
  - Completed independent test capabilities at Southwest Research Institute and preliminary validation of facility for sorbent materials.
  - Formed storage systems analysis working group and completed baseline independent analysis of sodium alanate system.

### *Future plans*

Following a report by the National Research Council (NRC), the DOE centres of excellence address the report’s emphasis on the importance of storage and its recommendation to “shift ... away from some development areas towards more exploratory work”, as well as the recommenda-

tion that “the probability of success is greatly increased by partnering with a broader range of academic and industrial organizations” (National Research Council Committee on Review of the FreedomCAR and Fuel Research Program, 2005). A thorough review of the centres of excellence was conducted in 2006 to develop lessons learned and apply them to other areas of the Hydrogen Program, as advised by the NRC. Continued funding at a low level for compressed hydrogen/cryogenic tanks emphasizes cost reduction and novel conformable designs. In addition, it is recognized that materials-based solutions will require low-cost, conformable tanks and would benefit from current R&D in this area. A major milestone in 2006 was the go/no-go decision on R&D for single-walled carbon nanotubes (SWNTs). The DOE decided to discontinue R&D on pure, undoped SWNTs for vehicular hydrogen storage applications. This decision was based on a previously established criterion that pure, undoped SWNTs had not met: achieving 6 per cent weight hydrogen storage at room temperature. However, there were certain areas of carbon nanotube research, such as metal-doped materials, that warranted additional R&D investment. In addition, an independent analysis of cryo-compressed tanks was conducted in 2006 to determine gravimetric and volumetric capacities as well as cost.

The R&D planned on metal hydrides will focus on the development of high-capacity materials, including complex hydrides, destabilized binary hydrides, alane, intermetallic hydrides, modified lithium amides and other new materials, using theory and combinatorial methods to increase the efficiency of materials identification and screening. The R&D planned on chemical hydrogen storage focuses on three “tiers” of R&D: borohydride-water, novel boron chemistries and innovation beyond boron such as liquid carriers. In the area of carbon-based materials, the planned R&D will focus on breakthrough concepts for storing hydrogen at room temperature, such as hybrid metal/carbon nanotubes and metal/fullerene hybrids, aerogels, nanofibres, metal organic frameworks and conducting polymers. A workshop on fundamental theory/modelling for hydrogen storage will be conducted in collaboration with the OSC, and closer collaborations with basic research activity are planned.

## Fuel cells

Fuel cells are an important enabling technology for the hydrogen economy and have the potential to revolutionize the way the nation is powered, offering cleaner, more efficient alternatives to the combustion of gasoline and other fossil fuels. Fuel cells have the potential to replace the internal-combustion engine in vehicles and provide power in stationary

and portable applications because they are energy-efficient, clean and utilize non-petroleum-based fuels.

The programme supports R&D of polymer-electrolyte-membrane fuel cells (PEMFCs), including fuel-cell stack components, fuel processors for stationary applications and balance-of-plant components. Transportation applications (direct-hydrogen fuel cells for vehicles) are the primary focus of the programme, since substituting domestically produced hydrogen for petroleum-based fuel in light-duty vehicles will significantly reduce US dependence on foreign oil, diversify energy resources and reduce pollution and greenhouse gas emissions. PEMFCs are currently the technology of choice for light-duty vehicles because they have fast-start capability and operate at low temperatures. The programme also supports stationary power, portable power (direct-methanol fuel cells) and auxiliary power unit applications.

### *Goal, objectives and key challenges*

The goal of the DOE programme is to develop and demonstrate fuel-cell power system technologies for transportation, stationary and portable applications. Key objectives of the programme, to be achieved by 2010, are to develop the technology base for the following.

- A durable, direct-hydrogen fuel-cell power system for transportation with a 60 per cent peak efficiency and a cost of \$45/kW if mass produced (and by 2015 a cost of \$30/kW).
- A distributed generation PEM fuel-cell system operating on natural gas or liquefied petroleum gas that achieves 40 per cent electrical efficiency and 40,000 hours durability at \$400–750/kW.
- A fuel cell for consumer electronics (<50 W) with energy density of 1,000 Wh/L.
- A fuel-cell system for auxiliary power units (3–30 kW) with a specific power of 100 W/kg and a power density of 100 W/L.

The DOE is working closely with its national laboratories, universities and industry partners to overcome critical technical barriers to fuel-cell commercialization. Cost and durability are the major challenges; size, weight and thermal and water management are also problematic. The programme continues to focus on materials, components and enabling technologies that will contribute to the development of low-cost, reliable fuel-cell systems. To address the key barriers of fuel-cell cost and durability, five new projects were initiated in 2005 at a cost of \$13 million over three years.

Targets, which vary by application, have been established for fuel-cell cost, efficiency, durability, power density, specific power, transient response time, start-up time and emissions, among others. The DOE multi-

year research, development and demonstration plan was updated in 2005: the major changes in the fuel-cell section of the plan were the removal of the target tables for on-board fuel processors resulting from the decision in August 2004 to discontinue those activities; the addition of target tables at the component level (membranes, electrocatalysts, membrane electrode assemblies, bipolar plates) to support the shift from systems development to R&D at the component level; and the addition of a hydrogen fuel-quality table.

Membrane electrode assemblies (MEAs) are the core of the fuel-cell stack and require excellent performance and very high durability to achieve automotive cost and performance targets. The DOE is working with industry to develop low-platinum, high-temperature (operation up to 120°C for transportation applications and up to 150°C for stationary applications) and low-humidity MEAs in parallel with high-volume manufacturing processes to meet cost targets. The DOE is pursuing advanced membrane R&D to improve durability and tolerance to feed-gas impurities, increase performance at low relative humidity and lower cost. Advanced catalyst R&D is targeting improved performance and lowered cost using low- or non-platinum catalysts.

### *Recent progress and status*

Significant progress was achieved in 2005 in catalyst development, membranes and bipolar plates. Specific recent accomplishments include the following.

- Durability testing at steady-state conditions and simulating a vehicle drive cycle, and characterized MEAs in situ by polarization curves and electrocatalyst surface area measurements (Los Alamos National Laboratory).
- Developed a membrane that can be mass produced, with conductivity comparable to Nafion, durability of >4,000 hours and, when incorporated into an MEA, platinum loading that is lower than the DOE's 2010 target (3M).
- Organized and conducted a workshop on fuel-cell operation at sub-freezing temperatures; demonstrated survivability for 40 sub-freezing cycles down to -40°C using cloth gas diffusion layers (Los Alamos National Laboratory).
- Completed the first phase of round-robin fuel-cell testing as part of the US Fuel Cell Council's efforts to develop single-cell testing protocols (Los Alamos National Laboratory).
- Demonstrated 20-fold improvement in Pt mass-specific activity of PtRe/Pd/C and Pt/Au/Ni/C catalysts over commercial Pt/C catalysts (Brookhaven National Laboratory).

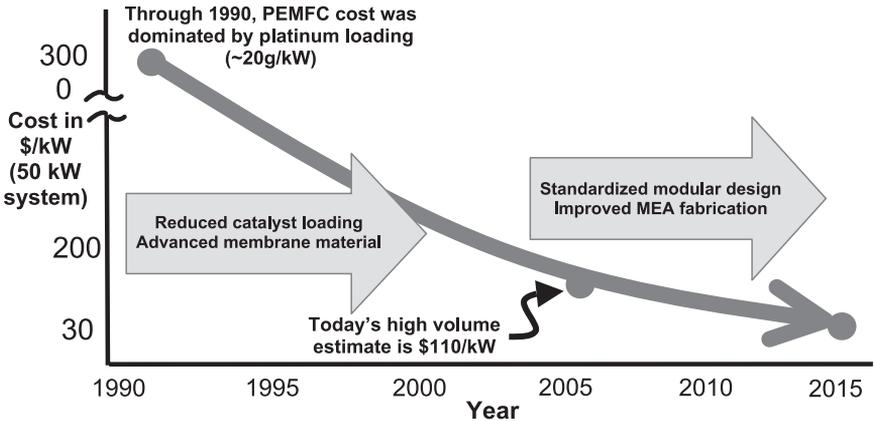


Figure 3.6 Estimated costs of 50 kW fuel-cell systems in high-volume production of 500,000 units per year

- Developed and validated an automotive fuel-cell system model, specifically targeting humidification systems and operation at sub-freezing conditions to guide the development of technical targets (Argonne National Laboratory).
- Identified the significant changes to the catalyst size and structure within an MEA after cycling and long-term fuel-cell operation using advanced microstructural characterization techniques (Oak Ridge National Laboratory).

Two key measures of fuel-cell progress are the cost for automotive fuel cells and the electrical efficiency for stationary fuel cells. Figure 3.6 illustrates the progress in fuel-cell cost reduction. For transportation applications, the 2005 estimated cost for high-volume mass production of a hydrogen-fuelled 80 kW automotive fuel-cell system was \$110/kW. This cost reduction was the result of increased power density, advancements in membrane materials, reductions in both membrane material cost and amount of membrane material required in the fuel cell, enhancement of specific activity of platinum catalysts and innovative processes for depositing platinum. For stationary systems, the 2005 target of 32 per cent electrical efficiency at full power was met for a natural gas or propane-fuelled 50–250 kW stationary fuel-cell system.

### *Future plans for fuel-cell R&D*

As recommended by the NRC (2005) report, the programme continues to increase government funding for high-risk R&D that can lead to breakthroughs in fuel-cell materials and component designs that lower costs, improve durability and increase reliability. The 2006 budget em-

phasized R&D on fuel-cell stack components (membranes, catalysts, bipolar plates, MEAs, etc.) while also supporting R&D for stationary fuel processors, balance-of-plant components and technical analyses.

Cost and durability of stack components continued to be a key focus of the research programme in 2006. Focus on characterization, evaluation and analysis to provide insights into fuel-cell operation, especially characterization of behaviour that leads to performance decay and failure, was emphasized. Additional research projects on high-temperature, low-humidity membranes were initiated. A solicitation (\$17.5 million available over five years) was issued for development of high-temperature ( $\leq 120^{\circ}\text{C}$ ), low relative humidity (25–50 per cent RH) polymer-electrolyte-type membrane materials suitable for use in a PEMFC. A second solicitation, with a broader scope, was released in 2006 to provide up to \$100 million over four years for fuel-cell R&D in several topic areas: improved fuel-cell membranes, water transport within the stack, advanced cathode catalysts and supports, cell hardware, innovative fuel-cell concepts, effects of impurities on fuel-cell performance and durability, and stationary fuel-cell demonstrations involving international and intergovernmental partnerships. The workshop on operation of fuel cells at sub-freezing temperatures, mentioned above, identified technical challenges and R&D needs related to start-up and operation of fuel cells at these low temperatures. Research in 2005 also helped to define problems and issues associated with cold-starts and the freeze-thaw cycle, which, combined with the workshop results, will help inform a focused R&D effort to address these issues.

## Safety, codes and standards

The federal government is in a unique position as a neutral third party to catalyse and coordinate the work of professional societies, trade associations and national/international organizations in development of codes and standards. The aim is to facilitate the creation and adoption of model building codes and equipment standards for hydrogen and fuel-cell systems in commercial, residential and transportation applications and provide technical resources to harmonize the development of international standards. In parallel, the focus for hydrogen safety is the development and implementation of practices and procedures that will ensure safety in the operation, handling and use of hydrogen and associated systems, and support the development of appropriate codes and standards. In 2006 the International Code Council (ICC) *ad hoc* Committee for Hydrogen Gas completed development of new hydrogen safety requirements (and modifications to existing requirements) for incorporation in the 2006 editions of the *International Building Code*, *International Fire Code*

and *International Fuel Gas Code*. These revisions incorporated all current data for high-pressure hydrogen storage and pressure relief devices. In addition, the DOE partnered with the Department of Transportation to advance an international effort to develop an R&D roadmap for a global technical agreement for hydrogen fuel cells, and to implement adoption of the agreement by 2010. Hydrogen education development is also planned to serve the needs of multiple target audiences, including state and local government officials, safety and code officials and local communities where hydrogen demonstrations are located.

## Infrastructure and technology validation

Testing and demonstration are essential for both fuel-cell vehicle and hydrogen infrastructure technologies to refocus research and validate laboratory progress and “readiness” for commercialization. The DOE awarded \$170 million for “learning demonstrations” that target testing, demonstration and validation of hydrogen fuel-cell vehicles, infrastructure and interfaces for complete system solutions. These 50/50 cost-shared projects bring together automobile and energy companies to demonstrate fuel-cell vehicles and refuelling infrastructure; their activities will identify “real-world” issues that will provide feedback to the R&D programme. These “learning demonstrations” will involve two generations of vehicles, compliance safety plans, methods to enhance the development of codes and standards and education and training campaigns. Such real-world projects are critical to help guide and refocus R&D activities.

## Partnerships

Transitioning the current petroleum fuel supply infrastructure to a hydrogen infrastructure will require extensive public-private cooperation due to the magnitude of technology challenges, costs, associated regulatory codes and standards and anti-trust issues. Under the FreedomCAR and Fuel Partnership, the DOE is collaborating with the US Council for Automotive Research (DaimlerChrysler, Ford and General Motors) and five major energy companies (BP, Chevron, ConocoPhillips, ExxonMobil and Shell) to help identify and evaluate technologies that will meet customer requirements and establish the business case. The programme’s technical and economic targets, created using input from technical teams of research managers from the DOE and the automotive and energy industries, represent customer requirements and the business case necessary for widespread commercial success. The technical teams meet regu-

larly to identify key critical barriers, update established roadmaps in each technology area and review research progress. Ultimately, it is industry which will primarily invest in building the automotive and energy infrastructure for the hydrogen economy. However, there is significant investment risk until hydrogen and fuel-cell technologies meet customer requirements and become economically competitive in the marketplace. Therefore, federal investment in high-risk R&D is necessary to address the critical technology barriers which reduce this risk. Much of the hydrogen research is cost-shared by academia and industry, reducing the costs to the taxpayers and indicating the private sector's commitment to the development of the hydrogen economy.

International collaboration is also a key element. The International Partnership for the Hydrogen Economy (IPHE), established in 2003, consists of 16 member nations and the European Commission. The IPHE provides a mechanism for partners to organize, coordinate and implement effective, efficient and focused international research, development, demonstration and commercial utilization activities related to hydrogen and fuel-cell technologies. It is a forum for advancing policies and common technical codes and standards that can accelerate the cost-effective transition to a hydrogen economy. Coordination through the IPHE will leverage scarce international RD&D funds, thereby reducing the cost of the hydrogen and fuel-cell research programmes of the IPHE partners through information sharing that facilitates efficiencies in their research and demonstration programmes.

## Looking towards the future

The Department of Energy is looking to the future. To increase the chances of success, it is partnering with the Department of Commerce and other federal agencies to plan a manufacturing R&D effort for the hydrogen economy. This activity will focus on ensuring that hydrogen products can be made in an economically viable manner in large quantities such that they will conform to design specifications, performance functionality, codes and standards, safety requirements and customer requirements.

## REFERENCE

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# Passion, purpose and partnerships: Building the hydrogen infrastructure

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*Gabriel F. de Scheemaker*

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## Introduction

The EU Hydrogen and Fuel Cell Technology Platform has concluded that early European markets could become established between 2007 and 2010 for fleet vehicles and portable fuel-cell applications, while large-scale stationary applications could achieve commercialization by 2015 and European mass-market transport applications before 2020 (European Union, 2005). Indeed, given the right support there could potentially be 1–5 million fuel-cell vehicles (FCVs) by 2020 globally, growing beyond 100 million between 2030 and 2040.

In short, a fully fledged hydrogen economy could be just over two decades away. But if we do not start *today*, 10 years from now it will *still* be two decades away. After all, the transition to mass production will require a massive overhaul of the energy infrastructure, and the success of this will depend entirely on significant public policy developments and funding.

Developing a hydrogen economy therefore requires visionary leaders – both in government and in business – who are passionate about making it happen; who can focus and keep their resolve. As a long-term solution to a long-term problem, it will require highly sophisticated levels of cooperation, coordination and commitment.

## Hydrogen today – A snapshot

For an energy company, dealing with hydrogen is of course nothing new. Shell has over 40 years' experience of using hydrogen in its refineries, where it handles more than 7,000 tonnes a day as part of a drive to produce ever-cleaner and better-performing traditional fuels. A dedicated unit, Shell Hydrogen,<sup>1</sup> was established in 1999 as a global business in order to pursue opportunities related to hydrogen and fuel cells in transport and distributed power applications. Its aims are threefold: first, to supply hydrogen in the most cost-effective way possible, in whatever form the markets want it; secondly, to support the development of technical solutions required to convert primary energies to hydrogen; and thirdly, to stimulate the development of technologies that will advance a hydrogen economy. It operates hydrogen stations in all the major hydrogen markets, and believes hydrogen can become an important element in the future energy mix, along with the cleaner traditional fuels and important advances such as modern biofuels and gas-to-liquids components.

In 2003 the very first publicly accessible hydrogen refuelling station in the world opened in Reykjavik, Iceland.<sup>2</sup> And since then various hydrogen stations for fuel-cell vehicles have opened, some as part of the Clean Urban Transport for Europe (CUTE) initiative – for instance in Amsterdam and Luxembourg.

In North America an “East Coast corridor” is being built, starting with a station in Washington, DC. This showcases the first hydrogen dispenser fully integrated at a regular retail gasoline station in the United States. A combined hydrogen/gasoline site, it demonstrates to people that hydrogen is nothing special: they can walk up to the pump, touch it and see hydrogen refilling taking place while they are refilling their own gasoline cars. In November 2007 the corridor was extended, with a station in the city of White Plains, New York.

On the West Coast, the California Fuel Cell Partnership, some 20 partners including automotive and energy companies, fuel-cell developers and government, not only operates an extensive public programme of events, but has opened a state-of-the-art facility serving 55 FCVs. Up to three new projects are now planned to open in 2008.

In Asia the Japan Hydrogen and Fuel Cell demonstration project (JHFC) has 12 refuelling stations serving 59 FCVs. The Ariake station that Shell operates is probably the most utilized hydrogen station in the world, having already serviced 2,000 vehicles from nine different auto manufacturers.

In China, following a feasibility study with Tong Ji University and two local Chinese partners, Shell has shared knowledge and expertise to help build Shanghai's first hydrogen station. Completed in 2007, it is the first

step to establishing a cluster of hydrogen stations, with over 1,000 Chinese FCVs planned by 2010.<sup>3</sup>

And finally in India, which has chosen a strategy of focusing first on the cheaper and simpler hydrogen internal-combustion engines, Shell has embarked on a feasibility study with Indian car companies such as Mahindra and Mahindra to make hydrogen available at integrated retail stations – hydrogen supply points that will form a hydrogen infrastructure no different from that required by future fuel-cell vehicles.

All this indicates that the industry will be able to bring hydrogen-powered FCVs to the point where both vehicles and fuel are attractive *and* affordable. Indeed, a clear vision of the road ahead is emerging. It is therefore time to take the next step; and that means implementing more realistic scenarios. Continuing to serve a handful of vehicles from single sites will not move us forward.

## Lighthouse Projects – The bridge to commercialization

The fastest and most cost-effective way to do this is via Lighthouse Projects – clusters of consumer-friendly retail sites where over 100 hydrogen vehicles from different car companies are served by more than four hydrogen stations. Operated by two or more energy companies and involving fleet owners, they would be run on a semi-commercial basis in international collaboration with government as public-private partnerships. As such, they will not only attract industrial commitment but also generate a critical mass of researchers and entrepreneurs, accelerate best practice and give confidence to the financial community.

Lighthouse Projects will thus play a crucial role in bridging the gap between the current demonstration projects and commercialization – a stepping-stone to a full commercial infrastructure rollout. They will obviously be much more efficient to run than the current stand-alone retail stations. They can also escalate in scale and sophistication, progressing from clustered integrated retail stations to clusters connected through corridors, as the infrastructure is steadily filled in.

By focusing initially on a *limited* number of Lighthouse Projects in North America, Western Europe and North-East Asia, we can build and test the strategies, disciplines and incentive mechanisms needed to coordinate activities for the next phase of development and enable the industry to grow. In fact, failure to do so could have serious consequences.

First, there is a real danger that if efforts are not focused, government funding and industry attention will become hopelessly fragmented, with valuable time being lost through duplication and reinventing the wheel. This is entirely possible – we have already experienced the issue of infra-

structure “earmarks”<sup>4</sup> in the United States; while in Europe there will be a strong push from all 25 individual member states to site activities in their own countries. But if the next move sees groups of five or six vehicles scattered in 100 locations around the world, we will end up going nowhere fast. Together, we need to work out where the early markets will be.

The second danger is that even if we get over the technology and mass-production hurdles for FCVs, we will run into a huge infrastructure “utilization hurdle” that significantly increases hydrogen supply costs. A series of scenarios, resulting from an internal Shell study of the rollout of vehicles and fuel infrastructure in a major metropolitan area, demonstrates this point clearly. In one, retail stations are located in areas and sites which do not stimulate good additional demand for FCVs and experience low facility utilization. In others, however, there is closer coordination with vehicle manufacturers on their anticipated customer needs and with local authorities on effective site development; and this is further exploited with effective utilization of facilities by realistic Lighthouse Projects. The result? A much clearer alignment of capacity with anticipated demand and more cost-effective matching of customer interests.

The model showed, not surprisingly, that a coordinated infrastructure rollout, which makes good use of existing manufacturing and retail assets, realizes much lower fuel supply costs – by up to a factor of two! The alternative is higher hydrogen fuel prices, which will simply discourage vehicle purchase. There is therefore a great need for mechanisms like larger-scale Lighthouse Projects which encourage coordination between governments and vehicle and fuel suppliers so that the industry can grow from its pre-commercial beginnings to the next phase of early commercial development.

But little can be achieved in isolation. We need international collaboration – substantial public-private partnerships, with a clear focus on commercialization. These will not only attract industrial commitment, but also accelerate best practice, attract investors, create markets and generate a critical mass of entrepreneurs. After all, it is the presence of sophisticated venture capitalists that transforms an opportunity into reality: attracting and providing capital and good management; nurturing start-up companies and linking them through the value chain; lobbying informally on the industry’s behalf; and handsomely rewarding investors and entrepreneurs, thereby attracting future capital. In short, keeping their eyes firmly on the commercial ball.

Venture capital funds will support and accelerate economic activity wherever Lighthouse Projects and hydrogen power plants are being developed. One can see such funds in action in North America and Europe, where they play an active role in a wide range of projects and technology

ventures. A New Energy venture capital fund has been set up in China, funded by a combination of large Chinese entities, such as the Science and Technology Commission of the Shanghai municipality, and multinational companies like Goldman Sachs and Shell. This fund will be co-managed by London-based Conduit Ventures,<sup>5</sup> which also managed the modest but successful hydrogen and fuel-cells fund Conduit I, and Chinese partners.

## Flagship energy systems – Integrating CO<sub>2</sub>, power and mobility

Of course, a hydrogen economy is not simply about transportation. With central production being the most economic route to supplying hydrogen at the pump, we should also accelerate experimenting with hydrogen-powered power plants and large-scale fuel cells. Initially using hydrogen turbines, these flagship energy systems could use Shell's proprietary gasification process to convert (carbon-intense) fossil fuels such as coal and produce hydrogen and CO<sub>2</sub> of high purity. In one large, integrated energy complex, hydrogen could be applied to generate low-emission power, hydrogenation of crude oil in refineries and hydrogen for transportation purposes, while CO<sub>2</sub> could be captured and stored, and in some cases could be used to enhance oil recovery. After resolving significant technical hurdles, this would be the next big step towards a new energy system based on hydrogen.

Hydrogen stations will be hydrogen supply points, but not just to fuel-cell vehicles. Micro-grids will also supply hydrogen to residential fuel cells, efficiently producing heat and power for domestic use. Metal-hydride cartridges can be exchanged here to power clean two- and three-wheelers, be they equipped with fuel cells or, initially, hydrogen internal-combustion engines. Stations will exchange or recharge hydrogen-based energy cartridges for portable and hand-held devices. The availability of 100 kW fuel-cell vehicles will give new meaning to distributed power generation, with their mobile power generator and energy storage devices flexibly deployed to refuel at home and also to power both residences and workplaces – wherever humans are active.

This will reduce the size of the energy infrastructure's required overhead and put to good use all power generating capacity, of which half is now dormant at any moment in time. Indeed, a new energy infrastructure based on hydrogen will not only introduce significant savings in the use of energy and capital investments, but it will reduce a nation's medical bill by providing a cleaner environment, thereby freeing up even more capital.

But let us come back from the future and concentrate on finding pathways to get there. Current activities and investment in creating a hydrogen economy focus on the developed areas of the world: mainly North America, Western Europe and Japan. Does this mean that developing countries will take a back seat?

## Issues for developing countries

Shell's recently issued "Global Scenarios to 2025" (Shell, 2005) includes trends for demography and energy demand growth. The world's population is likely to increase by 50 per cent in the first 50 years of the twenty-first century – from about 6 billion to about 9 billion. Some regions, however, will become more populous faster than others. This analysis shows that, despite net migration of about 2 million people each year into the developed countries, their share of the global population will steadily fall.

In Asia, population growth of 1.3 billion will also not prevent a slight decline (about 2 per cent) in its share of the world population. Meanwhile Africans – despite HIV/AIDS – will increase their share by nearly a third, from nearly 14 per cent to about 20 per cent of the world's population.

On a country-by-country basis, the shift in population share is noteworthy. For example, consider China growing from 1.28 billion in 2000 to 1.4 billion in 2050; and compare that with India, growing from 1.02 billion (i.e. 20 per cent fewer people than China) to 1.53 billion (i.e. nearly 10 per cent more people than China). The Russian Federation's population, on the other hand, is expected to decline by one-third within the same time period. In general terms, the developing world population is projected to increase from 81 per cent of the world total in 2005 to 84 per cent in 2025 and 86 per cent in 2050.

Previous scenarios observed a clear trend in urbanization, most notably in the developing world. This trend shows no signs of abating. In developed regions 75 per cent of the population already live in urban areas, and this is expected to rise to 80 per cent by 2025. In developing countries, however, the shift is much greater: from 43 per cent of people in 2005 to 54 per cent by 2025.

What makes this shift so significant is not the percentage rise, but the rise in *total* population in developing countries. This means that while the rural population will stay approximately the same, cities will have to absorb all the growth in the world's population. This will put increasing pressure on local capacity to provide clean water, housing and food –

not to mention education, healthcare and other services or public goods. This will, in turn, put increasing pressure on energy provision.

Growth depends on energy; and if the energy industry does not rise to the low-carbon challenge, it could stand in the way of world economic growth.

### *Developing countries and hydrogen*

A fit between this “highest tech” of mobility and energy technologies and the often “low-tech” reality of developing countries may be closer than is first apparent. In fact, in some areas it actually makes a lot of sense. It must be remembered that the predicted timeline for the hydrogen economy is long – it is at least 20 years away for developed countries. Developing countries can then implement it after developed countries have taken out the initial flaws – and having spent billions of dollars doing so.

New energy systems will develop from clusters, and hydrogen is particularly efficient in urban areas. These relatively low infrastructure investments will not only bring clean mobility, but clean energy as well. Indeed, in 20 years’ time the same amount of primary energy may transport someone over twice the distance – or, more pertinently, transport twice the mass – but with a significantly reduced environmental footprint.

Developing countries have another advantage: legacy assets often obstruct the deployment of new technology. Countries with little legacy technology embedded in their current energy infrastructure can actually leapfrog those with much more, skipping one or more generations of technology.

Could a new energy infrastructure based on hydrogen and fuel cells – developed over, say, a 30-year period – be the tool to modernize and diversify emerging economies and promote inclusive growth? A new industry, however, requires the presence of not just a healthy small and medium-sized enterprise sector, but an enabling environment characterized by political stability, property rights, rule of law, the right investment climate, financial services and products, and a transparent and stable legal infrastructure.

### *Designing a hydrogen roadmap*

Hydrogen is a long-term solution to a long-term problem, but if we do not start today, it will remain a long-term solution. While developed countries are implementing Lighthouse Projects, how can developing countries move towards a hydrogen economy?

This is a difficult question and the author does not know the answer. However, we do know where to start, and this is by designing a hydrogen

roadmap integrating all the expensive lessons that the developed countries have learnt.

What are these? Well, one thing is clear: *the vehicle is on the critical path* and the volume must go up – it is a condition for successful rollout. An effective component supply chain is therefore essential for vehicles and other applications to move down the cost curve towards mass production. This means giving component suppliers a realistic outlook on activity and investment levels over future years, while applications achieve the necessary performance and attractiveness criteria.

From a fuel provider's perspective, hydrogen distribution from central production must be developed as early as possible in order to address the issues of supply and distribution logistics. As developing countries will probably roll out later, and therefore with less uncertainty, they should be able to deal rapidly with relatively high volumes.

Then there is the public response. This can vary enormously – from enthusiastic to fearful – depending on how effectively public engagement has been conducted locally and how politicized the subject has become. For example, in communities like Iceland,<sup>6</sup> where support and desire have been built up over several years, implementation was swift. In Washington, DC, however, where the hydrogen project was originally greeted with both community *and* regulatory suspicion, significant delays and budget overruns resulted.

A hydrogen roadmap should therefore address *public awareness and education* as early as possible, so that there is a fertile ground of public support and regulatory experience when take-off does eventually become possible. Otherwise, progress will suffer long and unnecessary delays. This means informing key decisionmakers and future customers about the long-term benefits and near-term realities of hydrogen, fuel-cell systems and related infrastructure. We also need to work out a clear customer value proposition and address the barriers to social acceptance – town planning, health and safety issues, risk assessments, etc.

This will not only facilitate market acceptance and manage expectations, but help create the necessary human capital – researchers, technicians and engineers. It means establishing qualification guidelines for trade and industry, and engaging industry associations to coordinate and step up this activity.

But it is not just the public who need to have confidence in hydrogen, it is also investors. They need to see both *a transparent legal infrastructure* and *a stable environment*. For example, what will regulations, codes and standards look like, and what permits will be required? What taxes will this industry face and in what form? What incentives will be put in place and for how long? A government's public commitment that hydrogen vehicles will not attract taxes for, say, the next 25 years will go a long way in

stimulating development and attracting activity, probably without missing out on net fiscal revenue. Also, we should not lose the opportunity to develop and apply incentives to reduce CO<sub>2</sub> emissions in the broader policy arena.

In short, there must be a clear line of sight to normal – competitive – commercial operation in order to build confidence in hydrogen’s long-term viability. It means having a coherent framework of incentives and regulations that crosses different countries – reducing risk and “friction”, and providing a focus for industry development. Clarity on fiscal and other long-term economic incentives is therefore essential for establishing credibility – stimulating infrastructure investment, building up vehicle demand and establishing supply chains – while the economies of large-scale production build up. Naturally, these incentives will be structured to reduce as progress allows, but it must be clear how this will happen.

*Intellectual property rights* are crucial for encouraging new technology and protecting investment in R&D, while discouraging broad claims which can delay development. IP rights should be considered in the context of internal – particularly American and Japanese – patent practices.

## CO<sub>2</sub> – A big business opportunity

During the early rollout stages of hydrogen as a transportation fuel it will mainly be made from natural gas, which will be available from existing hydrogen production facilities, such as refineries and gas production sites. When FCV penetration takes off, new production facilities will be built – mostly in the form of semi-central production sites – but still using natural gas and coal as feedstock.<sup>7</sup>

Central manufacturing is not just the lowest-cost method to deliver hydrogen to the customer at a retail site, but it will also enable up to 90 per cent carbon capture and sequestration, heralding the “clean” hydrogen phase. For quite some time hydrogen and CO<sub>2</sub> will be two sides of the same coin, so we need to set targets for the latter and create incentives for its capture and storage. Shell is capturing and storing CO<sub>2</sub> in demonstration projects now, but still needs to see if it can be done on a larger scale. It will take a decade to test the carbon-capture technology. According to Shell’s CEO, Jeroen van der Veer, “And then we have to work things out with governments so we can make it [economically] worthwhile, because right now if you capture CO<sub>2</sub>, you don’t get credit for it, which just isn’t logical. A unit stored should be the same as a unit saved” (*US News & World Report*, 2007). Yet even without sequestration, there are modest CO<sub>2</sub> advantages to using hydrogen thanks to energy efficiency improvements. Natural gas and coal will not be replaced

by renewables as feedstock until the turn of the century, and there are important reasons for this.

Solar and wind generally produce electricity, but it will be many years before non-fossil power is able to meet all electricity demand. Indeed, by 2050 it is estimated that 50 per cent will still be generated from fossil resources. There are therefore strong arguments for using renewables *directly* for electricity instead of converting the electricity to hydrogen, which is less energy-efficient.

However, in certain regions and at certain times the excess electricity from renewables can sensibly be converted to hydrogen. We may see this first after wet seasons and on islands, such as Iceland or Tasmania. “Green” hydrogen will thus develop from locations which particularly favour renewables. Ultimately, and in regions where electricity demand is already mainly supplied by renewables, more and more may be used to produce hydrogen. It may take 30–50 years before improvements in conversion efficiencies shift this paradigm.

## Effective hydrogen roadmaps

Above all, hydrogen roadmaps must underline the importance of *a clear, coordinated focus on commercialization* by all relevant parties. In fact, it is essential if we are to attract investors and convince them that a hydrogen economy can be not only cost-effective but highly profitable – the carrot for all entrepreneurs.

The author believes that 80 per cent of individual roadmaps have common content, and that an institution such as the United Nations University can play a vital role in building a template for hydrogen roadmaps. The main players in this fledgling industry are certainly keen to support this effort by communicating the latest lessons learnt. They are equally keen to develop relationships with their industrial partners of the future, augmented by visionary investors and funds managed by firms that are expert in the hydrogen and fuel-cell industry.

As with many of the issues that are facing developing countries, the creation of a new energy infrastructure will not be easy. But with passion, purpose and partnerships, we will surely find a way.

## Notes

1. See [www.shell.com/hydrogen](http://www.shell.com/hydrogen).
2. For a discussion of Icelandic New Energy and the ECTOS project see chapter 9 in this volume.

3. For additional information on the hydrogen infrastructure in China see chapter 15 in this volume.
4. By “earmarks” is meant politically motivated conditions to incentive schemes, for instance favouring certain regions, technologies and collaborations that industry would normally not have chosen.
5. See [www.conduit-ventures.com](http://www.conduit-ventures.com). Conduit Ventures is regulated by the UK Financial Services Authority.
6. See chapter 9 this volume.
7. On coal gasification and hydrogen in South Africa see chapter 17 in this volume.

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## Part II

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# Making choices about hydrogen and fuel cells for sustainable transport

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# Introduction

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Population growth, urbanization and industrialization are driving a significant increase in private automobile ownership in the developing world. Urban pollution has thus risen dramatically in many of these countries, and ways to reduce the use of petroleum in the transport sector are now high on the agenda. So, too, is the need to rethink earlier transport strategies which consciously or inadvertently created incentives for the choice of private motor vehicles over public transportation systems for urban, regional and long-distance transport. For oil-producing countries, the present situation provides a windfall for those exporting crude. But the future is uncertain and will require some new thinking. This part of the book takes a closer look at these broad issues, with particular emphasis on how countries are making choices about alternative fuels and disruptive energy technologies such as hydrogen and fuel cells, alternative uses for oil and gas and alternative strategies for the transport sector.

Growing urban pollution and the impact of CO<sub>2</sub> on climate change have led to a chorus of conflicting views on the use of “cleaner” fuels in the transport sector. Initially attention focused on the introduction of natural gas, especially in fleets of urban vehicles. The conversion of buses to CNG in New Delhi and other cities in the developing world was heralded as a great triumph in this respect. But the costs of conversion are prohibitive in those countries where natural gas is not available or easily accessible.

Rising demand for oil and gas, moreover, has led developing countries to invest further in the expansion of oil and gas production. But this

provides few incentives for oil companies in the developing world to add value to oil and gas through downstream processing into petrochemicals or more innovative uses, and it does little to change existing consumption patterns worldwide, even with oil at US\$100 per barrel.

One response to this recommitment to a carbon-based economy was the shift in focus to renewable fuels such as ethanol. With the successful elimination of subsidies for the production of ethanol from sugarcane and the development of flexible-fuel engines, Brazil emerged as the world's leading producer of bio-ethanol. Many developing countries are following suit. The Renewable Energy Division of the Nigeria National Petroleum Corporation, for example, has created an automotive biomass ethanol programme based on sugarcane and cassava.

Ethanol production, however, has generated increasing criticism on a number of counts. First is the impact that a growing market for biofuels can have on land-use patterns, notably the destruction of forests to provide space for crops that can be used as feeder stock for ethanol production, such as sugarcane and palm oil, and the tendency towards intensive plantation agriculture in their production. Second are the distortions that subsidization of either ethanol production and/or ethanol use creates in the incentives to grow food crops, such as maize (corn) and soyabean, for use in ethanol production. Both a glut in the supply of ethanol and upward pressure on food prices have resulted. Third are the questionable energy gain and pollution reduction that result from the carbon-based inputs such as fertilizers used to grow the corn, the carbon dioxide emitted by the yeast to convert the cornstarch into sugar and the use of coal or natural gas to create the steam that drives the distillation process.

Although the production of ethanol from sugarcane has some environmental advantages over corn, to promote sustainable development in social and economic as well as environmental terms Brazil has invested in the development of new technology for the production of biodiesel. Petrobras, Brazil's state-run oil company, began marketing biodiesel in late 2007 and will open three new biodiesel plants in March 2008. Ten additional plants are scheduled to be built by 2012, bringing biodiesel capacity from the current 48 million gallons to 225 million gallons a year.<sup>1</sup> In addition to being a clean technology, biodiesel opens new opportunities for smallholders to enter this market through the production of a wide variety of feeder stocks. Production decentralized to local and regional levels has the added advantage of reducing the costs of long-distance transportation for plantation-grown sugarcane, the main feeder stock for ethanol production in that country. China, the world's third leading producer of ethanol after Brazil and the United States, has now abandoned future ethanol projects that use food feedstock in favour of *jatropha* cultivation that does not compete with food crops, while firms in the

United States and Canada are turning to research on cellulose-feedstock-processing technology which can use waste products or grasses that can be grown on low-grade soil.

The potential introduction and widespread use of disruptive technologies such as hydrogen and fuel cells add yet another dimension to the issues surrounding the choice of fuels and alternative transportation policies. The uncertainties surrounding the date for the likely commercial introduction of hydrogen and fuel-cell vehicles shape the long- versus short-term parameters within which developing countries must make choices about the continued use of existing fuels and transport modes, moving into transitional technologies such as CNG or ethanol that would require substantial investments or taking a leap into an uncertain hydrogen future.

A number of countries are giving these issues considerable thought, and what seems to be emerging is a variety of new energy and transport options that take a broader, more flexible and longer-term perspective. Diversification of energy portfolios, modes of transport and points of entry into a hydrogen economy are illustrative of this change and show how it is possible to maximize learning and positive development impacts along with reducing greenhouse gases (GHGs). Iceland and Egypt provide two interesting examples.

Some 70 per cent of Iceland's energy needs are met by thermal and hydropower. To cut GHG emissions still further, Iceland is exploring the use of excess electric power to generate hydrogen through electrolysis and then reacting the hydrogen with CO<sub>2</sub> and CO emissions from aluminium smelters and other heavy industry in that country to produce synthetic hydrocarbon fuels. Synthetic fuels produced in this fashion are carbon-neutral and thus have an advantage over synthetic fuels produced from carbon-based inputs such as coal that would require carbon sequestration technologies still in their infancy (see part IV of this volume).

Making choices about pollution abatement in the transport sector often pits speed against longer-term learning and development advantages. Egypt is avoiding dichotomies such as these by creating an integrated transport strategy. Egypt already has extensive experience in the production of hydrogen through both electrolysis and natural gas reforming. Along with its natural gas distribution network, the country has a good foundation for a later move to hydrogen. Egypt is also a manufacturer of buses, and with the proper incentives could use this set of local energy resources and capabilities to reduce urban pollution significantly. From this perspective, Egypt chose CNG bus demonstration projects for Cairo over the much more costly and not immediately commercializable hydrogen fuel-cell bus demonstration projects, such as those under way in Iceland, China and Brazil. The decision to build a long-term sustainable

transport sector has thus led Egypt to lay the basis for hydrogen and fuel-cell technologies in the future by maximizing learning from related technologies in the present.

## Note

1. See [www.biofuels-news.com/news/petrobas\\_10.html](http://www.biofuels-news.com/news/petrobas_10.html).

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## 5

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# Alternative transport fuels in developing countries and implications for approaching hydrogen

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*Grant Boyle*

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### Introduction

Hydrogen and fuel cells appear to be a promising solution for developing and developed countries alike. Developing countries suffer from far greater transport pollution problems, and are projected to overtake OECD countries in greenhouse gas emissions in the next two decades. Oil dependence is on the rise in many of these countries as they move away from “traditional biomass” energy resources into fossil fuels, particularly in transport, and many developing countries are interested in participating in the commercialization of new technologies.

However, in the short term hydrogen fuel cells do not typically emerge as the best solution for meeting environmental goals. For example, higher emissions standards for conventional ICE vehicles and higher-quality gasoline and biofuels such as Ethanol and biodiesel are relatively lower-cost solutions that can be taken over the short term to reduce urban air pollution, and these standards are likely to come into effect in many developing countries in the coming years, as chapter 6 in this volume illustrates. Similarly, better efficiency standards for conventional vehicles, including hybridization, and improved public transport and demand management are key solutions for reducing greenhouse gas emissions and oil dependence in developing countries. In terms of industrial development opportunities, the market for ethanol and biodiesel blending in gasoline and diesel presents an immediate opportunity for many developing countries. In this regard, over the short term interest from

these countries in hydrogen and fuel cells will be driven primarily by longer-term technology and sustainable energy planning rather than by short-term goals associated with oil dependency, air pollution or emerging greenhouse gas reductions – a point raised in chapter 8 in this volume. Still, it is important for developing countries to monitor hydrogen development and map their engagement strategically.

A useful source of guidance for understanding the role of hydrogen and its potential opportunity and path of emergence is the experience that developing countries have had with alternative fuels thus far. There is already a wealth of experience to draw upon, as some of the largest and most successful alternative fuel programmes to date have taken place in the South. This chapter provides an overview of the policy drivers of alternative transport fuels, the status of commercial alternative fuels in developing countries and a framework for understanding the key mix of conditions that have tended to catalyse the deployment of these fuels in developing countries to date.

## Drivers of alternative transport fuels in developing countries

About 95 per cent of transport fuel demand in the world is met by oil. Alternative fuels like compressed natural gas, liquefied petroleum gas, ethanol, biodiesel and electricity comprise only niche markets in both developed and developing countries, but are receiving increased attention for a number of reasons: local air pollution, greenhouse gas emissions, oil dependency and imports, and industrial innovation and employment.

### *Local air pollution*

Increased local air pollution from the combustion of gasoline and diesel in transport and the related health impacts from particles, carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>) and sulphur dioxide (SO<sub>2</sub>) are of particular concern for many cities in developing countries where the levels of NO<sub>x</sub>, CO, hydrocarbons and particulates exceed World Health Organization guidelines by significant margins. CO, emitted when fuels containing carbon are burned incompletely, poses serious health threats, particularly to foetuses and people with heart diseases, by hindering oxygen transport from the blood to body tissue. Nitrogen dioxide (NO<sub>2</sub>) has been linked with increased susceptibility to respiratory infection, increased airway resistance in asthmatics and decreased pulmonary function.<sup>1</sup> Particulate matter (PM), discrete liquid or solid particles of different sizes, can be directly emitted from fossil-fuel combustion or result from transformations of gaseous emissions like NO<sub>x</sub> and SO<sub>2</sub>. Particulates aggravate respira-

tory and cardiovascular disease.  $\text{NO}_x$  and  $\text{SO}_2$  are also key agents of acid deposition (acid rain). Gaseous air toxins, like benzene, are considered human carcinogens, and lead impacts on the intellectual development of children.

Generally, conventional air pollutants in the absence of advanced pollution controls and standards rise in direct proportion to increased energy use. Motorization in transport is a major contributor to increased emissions of these pollutants. In recent years rapidly motorizing Asian cities have experienced particularly sharp rises in air pollution from transport.<sup>2</sup>

Conventional air pollutants have been significantly reduced in many industrialized countries over the last few decades with improved fuels, engine technology, engine efficiency and engine after-treatment technology. Many developing countries are following a similar path by introducing higher standards (such as EURO standards) for new vehicles and improving gasoline and diesel quality. Leaded gasoline, for example, is being phased out in most of the developing world. Many developing countries are now looking at reducing sulphur in gasoline and diesel in order to reduce local emissions and enable the use of engine after-treatment technologies (such as advanced catalysts and particulate filters) that would be inoperable with high-sulphur fuels. However, financial challenges, low vehicle turnover rates, the practice of importing older vehicles from the North<sup>3</sup> and weaker enforcement institutions in developing countries may delay the control of conventional pollutants in the South. Many analysts agree that cleaner fuels (including alternative fuels) and vehicles need to be taken up, along with inspection and maintenance regimes and integrated transport planning, in order to deal with urban air pollution comprehensively.

### *Greenhouse gas emissions*

Climate change<sup>4</sup> is emerging as a major, long-term global threat that is projected to have negative impacts for developing countries, including impacts on agriculture and food production. Climate change results from emissions of greenhouse gases – mainly  $\text{CO}_2$  released in the combustion of fossil fuels.  $\text{CO}_2$  emissions are distinct from conventional pollutants in both the scope and the nature of the impact on human health and environment. Conventional pollutant impacts are more immediate and localized (respiratory health/acid rain), whereas greenhouse gas (GHG) emission impacts are more delayed and global (global climate and ecosystem instability/sea-level rise/food production). While higher efficiency standards and other measures can be taken to reduce  $\text{CO}_2$  emissions from in-use vehicles, “tailpipe” technologies like catalytic converters or other

Table 5.1 Energy-related CO<sub>2</sub> emissions (million tonnes)

	OECD		Developing countries		World	
	2002	2030	2002	2030	2002	2030
Transport	3,384	4,856	1,245	3,353	4,914	8,739
Total	12,446	15,833	8,226	18,365	23,579	38,214

Source: IEA (2004a).

devices that are used to reduce or nearly eliminate conventional emissions are not yet available for CO<sub>2</sub>.

As of 2000 emissions from transport-related activities accounted for around 20 per cent of GHG emissions<sup>5</sup> worldwide. According to the International Energy Agency (2004a), developing countries are expected to contribute more than two-thirds of the increase in global CO<sub>2</sub> emissions over the next three decades and to surpass the OECD as the leading contributor in the early 2020s. An increasing share of these emissions will come from transport. The *World Energy Outlook* (ibid.) projects CO<sub>2</sub> emissions from transport will grow by approximately 170 per cent from 2002 to 2030 in developing countries, compared to 43 per cent in OECD countries over the same time period (table 5.1).

Although improvements in efficiency are expected to reduce CO<sub>2</sub> emissions per kilometre travelled (especially in industrialized countries where more efficient technologies may first be deployed), these improvements will probably be offset by both increased utilization and increased numbers of vehicles. According to the World Business Council for Sustainable Development (2004), total annual passenger-kilometres are expected to grow over the next 30 years on average by 3 per cent per year in China, 2.8 per cent in Latin America and 1.6 per cent in Africa. Vehicle ownership rates in China and Latin America are projected to rise to current OECD levels (approximately 500 vehicles per 1,000 people) by 2050, which would result in approximately 5 billion vehicles worldwide compared to the current 1 billion.

Analysts and policymakers have promoted a range of solutions to address GHG emissions from transport. Solutions include transport planning measures like linking urban development and land use with transport to improve access to goods and services while reducing the need to travel, improving options for non-motorized transport and public transportation, and promoting modal shifts to rail for freight transport, as well as more technological solutions related to improved fuel efficiency,

fuel and vehicle quality, inspection and maintenance and the use of bio-fuels and other alternatives, including hydrogen (ADB, 2006).

### *Oil dependency and energy imports*

Oil dependence and expensive oil imports are a major concern for developing countries and a key driver of energy policy, particularly since so few countries possess oil reserves and the price of oil has increased dramatically in recent years. In 2030 the transport sector will account for 54 per cent of global oil consumption, compared to 47 per cent now and 33 per cent in 1971, and the bulk of the growth is projected take place in developing countries (International Energy Agency, 2004a). South and East Asia's share of world energy demand in transport is projected to grow from 11 per cent in 2000 to almost 30 per cent in 2030, and China is expected to account for 12 per cent of total transport energy demand by 2050. At the same time, the Asian region's oil import dependence is expected to double from 43 per cent to 78 per cent in 2030, marking significant increases in oil imports in coming years for Asia's developing countries (table 5.2). And by 2020 India's oil imports are expected to rise from 70 per cent to 85 per cent of consumption, also indicating increased energy dependence.

In addition, high oil prices have significant impacts on the fiscal positions of many developing countries that rely heavily on oil imports or subsidize domestic fuel consumption and/or regularly intervene to shelter their economies from price shocks. Indonesia, for example, which has long subsidized domestic fuel consumption, has faced increasing subsidy costs with rising world oil prices. In 2004 the Indonesian government originally planned to spend 14 trillion rupiah (\$1.5 billion) on fuel subsidies. As the oil price rose, the bill more than quadrupled, to 63 trillion rupiah (*The Economist*, 2004). Indonesia, Nigeria and Iran (also

Table 5.2 Oil import dependence in net importing regions (%)

	2002	2010	2020	2030
OECD	63	68	79	85
Developing Asia	43	59	72	78
China	34	55	68	74
India	69	80	87	91
Other Asia	40	54	68	76

Source: IEA (2004a).

oil-producing countries with traditionally low fuel prices but limited domestic refining capacity) face significant costs related to importing higher-priced fuels bought on the world market and maintaining low domestic prices.<sup>6</sup>

The production and use of alternative fuels have become a key solution to reduce oil imports and save foreign exchange reserves. In the case of the Brazilian ethanol programme, which was originally prompted by high oil prices in the 1970s, it has been estimated that the use of ethanol in transport led to foreign exchange savings of \$18 billion (in 1990 US\$) from 1978 to 1990 (La Rovere, 2005). The high price of oil in the 1970s and the balance-of-payments crisis in the country were probably the primary drivers of the Brazilian programme.

### *Industrial development and employment*

The industrial development and employment opportunities in the development of the alternative fuels industry are also important, especially when considered in conjunction with the costs of foreign oil dependency. In a number of developing countries with oil resources, a primary step towards further innovation is developing refining capacity to provide automotive fuels domestically rather than relying on imports. Oil-producing countries that rely on refined-product imports include Indonesia, Viet Nam, Nigeria and Iran.

Many developing countries have invested in CNG and a growing number are interested in biofuels. The often-cited success story of the Brazilian ethanol industry demonstrates the potential gains in industrial development, exports and employment in the alternative fuels sector. The Brazilian ethanol programme (Proálcool) is the largest commercial application of biomass for energy production in the world, accounting for 70 per cent of the world total biofuel transport market. The programme has led to the creation of 720,000 direct jobs and more than 200,000 indirect jobs in rural areas – a significant outcome in Brazil, although there has been criticism of the social conditions of workers. Industries involved in the programme have also seen large productivity gains over its course.

Similarly, the natural gas vehicle industry has had important benefits for Argentina and other countries with natural gas programmes. The programme in Egypt is credited with the creation of 2,500 new jobs. Biofuels also represent an important potential industrial opportunity for developing countries, which often possess the best climatic conditions for biofuel crops. In addition, biofuel production can be adapted from existing agricultural industries and capacities in many developing countries.

Table 5.3 Possible fuel/propulsion-system combinations

	Spark ignition	Compression ignition	Fuel cell	Reformer + fuel cell	Electric motor
Gasoline	*			*	
Diesel		*		*	
CNG	*			*	
LPG	*				
Hydrogen	*		*		
Methanol	*	*	*	*	
Ethanol	*	*		*	
Biodiesel		*			
DME		*		*	
Electricity					*
F-T		*		*	

Source: Frost and Sullivan (2004).

## Alternative fuels and their status in developing countries

There are a number of different fuels and fuel-propulsion-system combinations (table 5.3). Here the chapter considers alternative fuels to gasoline and diesel that have seen some commercial market penetration: natural gas, liquefied petroleum gas, electricity and biofuels.

### *Natural gas*

Natural gas is comprised primarily of methane, which has a higher hydrogen-to-carbon ratio than gasoline or diesel and a higher octane number, permitting engines that operate at high compression ratios. Natural gas offers significant reductions in local air pollutants, especially particulate matter, compared to conventional diesel vehicles. World supplies of natural gas exceed proven oil reserves by 22 per cent, and natural gas requires very little processing for automotive use. Countries that already have natural gas distribution infrastructure can introduce gas as a vehicle fuel relatively easily by installing refuelling appliances in grids. Without grids, road tankers must be used in large numbers.

Gasoline and diesel vehicles need to be retrofitted for natural gas unless new vehicles are used. Natural gas vehicles can be bi-fuel vehicles (which can run on either gasoline or natural gas); dual-fuel vehicles (which run on a mixture of diesel and natural gas); and dedicated vehicles (which run entirely on natural gas). Natural gas vehicles are typically more expensive and have shorter driving ranges than conventional

Table 5.4 Top 15 natural gas programmes in developing countries

Country/ programme	Vehicles	Refuelling stations	Last updated
Argentina	1,413,664	1,342	January 2005
Brazil	1,000,000	1,342	April 2005
Pakistan	600,000	670	February 2005
India	204,000	198	April 2004
China	69,300	270	April 2003
Egypt	52,000	79	April 2004
Venezuela	50,000	140	January 2004
Colombia	43,380	78	September 2004
Bangladesh	31,988	79	December 2004
Iran	22,058	40	December 2004
Bolivia	28,790	59	May 2005
Malaysia	12,000	38	October 2004
Chile	5,500	13	March 2005
Indonesia	4,660	28	December 2001
Thailand	4,905	31	May 2005

Source: IANGV (2005).

vehicles. As of 2003 there were more than 3.3 million natural gas vehicles and almost 7,000 refuelling stations worldwide (table 5.4). Italy, Argentina, New Zealand, the Russian Federation and the United States have significant natural gas vehicle fleets, as do Brazil, Pakistan, Egypt, India and China in selected cities.

### *Liquefied petroleum gas*

Liquefied petroleum gas (LPG) is a mixture of light hydrocarbons, mainly propane/propenes and butanes/butenes. Sixty per cent of LPG in the world today is produced through extraction from natural gas or from crude oil streams coming from underground reservoirs, and 40 per cent is extracted in the refining of crude oil. LPG generally has lower conventional emissions but similar NO<sub>x</sub> emissions to gasoline vehicles; it has a high octane number (especially propane), permitting higher compression ratios than gasoline engines. Most LPG vehicles replace gasoline vehicles. The main potential problems in introducing LPG to the transport sector have to do with stability of supply and the distribution system. Special refuelling equipment is needed to transfer the pressurized liquid from storage tanks to the vehicle and ensure that no LPG escapes during refuelling: such facilities are already in use on a large scale in the Netherlands and Italy. LPG is also used in significant amounts in Japan, North

Table 5.5 Selected developing country users of LPG in transport, 2000–2002

Country	Consumption (000 tonnes)
Mexico	1,260
China	450
Iran	318
Thailand	229

Source: GAIN (2002).

America, Mexico, Turkey, Hong Kong, China, Iran and Thailand (table 5.5).

### *Biofuels*

The two most commonly used biofuels in vehicles are ethanol and biodiesel. Ethanol-blended gasoline or “gasohol” at 5–10 per cent ethanol-blended gasoline is a common concentration. Pure ethanol is used only in the Brazilian Proálcool programme, which uses specialized engines.<sup>7</sup> Ethanol has high octane and relatively clean combustion characteristics. The presence of oxygen in ethanol facilitates combustion, reducing CO and hydrocarbon (HC) emissions; however, the emissions of aldehydes, which are toxins, are higher from ethanol than from conventional fuels. CO<sub>2</sub> emissions vary, and depend on life-cycle emissions.<sup>8</sup>

Ethanol can be produced from many biological feedstocks, including sugarbeet, sugarcane, corn and other cereals, as well as potentially cellulose materials: grasses, wood and various waste products are common examples. Alcohol can be used in gasoline vehicles at blends of up to 20 per cent, provided rubber parts are replaced in older vehicles. Distribution is similar to gasoline, but requires installation of alcohol-resistant materials along the fuel chain.

Biodiesel is produced by reacting vegetable or animal fats with alcohol to produce a fuel similar to diesel; it comes mainly from rapeseed, soybean, sunflower and palm. Engines running on low-level blends of biodiesel tend to have lower CO emissions but higher NO<sub>x</sub>. CO<sub>2</sub> emissions vary depending on production. Biodiesel may have negative side-effects on engine and refuelling components unless precautions are taken, but biodiesel and diesel have no major differences in infrastructure requirements. A significant barrier to biofuels is the land area required for feedstock.

Global biofuel consumption in transport was 8 Mtoe in 2002, representing 0.4 per cent of total transport fuel consumption worldwide.

Table 5.6 Biofuel activities in selected developing countries

Country/programme	Biofuel production/consumption
Brazil (Proálcool) Phase 1 1970–1990	By 1990: approximately 10 billion litres of ethanol consumed per year By 1990: approximately 25% of car fleet (3–4 million vehicles) using neat ethanol; remaining vehicles used 22–26% blends
Brazil (Proálcool) Phase 2 1990–present	2002: 5.5 billion litres of ethanol used in gasoline blends 2002: 32% of new cars were 100% ethanol 2004: 26% of new cars flex-fuel, running on any mixed proportions of gasoline and ethanol
China	Annual ethanol production of 3 billion litres (for all purposes), primarily from corn Largest biofuel plant in world
India	Undertaking 10% ethanol-blended gasoline trials 2000: 1.7 billion litres of ethanol produced (for all purposes) 2003: about 220 retail outlets sold 11 million litres of ethanol for blending with gasoline
Malaysia Ghana	About 6,000 litres per year of palm-oil biodiesel 2004 plans for 360,000 tonnes annually of biodiesel from physic nuts (jatopha)

Source: IEA (2004b).

Seventy per cent of the world total consumption takes place in Brazil, where ethanol has been produced from sugarcane since the 1970s and where the fuel accounts for 30 per cent of local gasoline demand (table 5.6).

The second-largest producer of ethanol is the United States, with around 23 per cent of the global share. Biodiesel production is highest in Europe, where more biodiesel is produced than ethanol, but total production of both fuels is fairly small compared to production of ethanol in Brazil and the United States. The main biodiesel-producing countries are France, Germany and Italy, where the fuel is used as a diesel blend (5 per cent or 20 per cent). In Germany biodiesel is commonly sold “neat” (100 per cent).

China and India are beginning to produce significant amounts of ethanol for fuel blending. The Philippines is investing in coconut biodiesel, equivalent to about 1 per cent of diesel fuel use in the country. Malaysia is gearing up for greater production of palm-oil biodiesel production. A number of African countries have begun to experiment with the production of biodiesel from physic nuts (jatopha). In Colombia the government approved a law requiring cities with populations exceeding 500,000

to add 10 per cent ethanol to gasoline beginning in 2006. India and Thailand have incentive programmes.

### *Direct electric propulsion*

In electric propulsion, a vehicle uses batteries to power an electric motor. Electric vehicles produce no emissions during operation. For public transport vehicles, use of external current is well established, while for private automobiles battery electric vehicles have encountered problems with slow recharging, cost and driving range, and have received less attention than hybrid gasoline-engine/electric vehicles in recent years. Battery-driven three-wheeled vehicles occupy small segments of urban transportation systems in India and Nepal. Lead-acid batteries are currently used as a low-cost option; nickel-metal hydride and nickel-cadium have greater driving range, but are more expensive. The economics of electric vehicles also depends on the local cost of electricity. Electric batteries must be recharged by plugging the vehicle into a power source and may take between two and eight hours to replenish, depending on the power of the charging system. Some vehicles have on-board chargers, while others plug into a charger located outside the vehicle, but both must use electricity that comes from the power grid to replenish the battery. Electric batteries have a limited number of charging cycles – and typically need to be replaced every three to six years.

### Factors influencing market deployment

Despite their benefits, alternative fuels and vehicles are typically more expensive than conventional fuels and vehicles. They face significant barriers, like new and different fuelling infrastructure, insufficient codes and standards, increased maintenance costs and technical support requirements, underdeveloped financing mechanisms, unestablished consumer support and so forth. As such, there are some important lessons to be drawn from the developing country experience to date with alternative fuels in trying to understand how new and existing alternative fuels, including hydrogen, are likely to enter the market.

Alternative fuel markets tend to develop as niche markets in the context of gasoline and diesel markets and tend to be supported by conditions that are unique to each country case. The factors that are particularly catalytic in the deployment of alternative fuel programmes in developing countries to date are categorized as local energy resources, supportive pricing policy and political commitment, history of related innovation and supportive social attitudes and perceptions.

*Local energy resources*

The local endowment of energy resources is clearly an important factor determining the market development of alternative fuels. Countries with alternative fuel programmes typically possess domestic alternative fuel resources and lack conventional oil reserves. Countries that have natural gas vehicle programmes typically possess significant gas reserves, like Pakistan, Argentina, Egypt and Iran, or significant production capacity, like India. Brazil has abundant sugarcane to support ethanol production, and Nepal has significant hydroelectric resources to fuel its battery-operated three-wheeled vehicles. Emerging biofuel production programmes in developing countries are also based on local agricultural resources. Examples include ethanol from corn in China and sugar and tapioca in Thailand, and biodiesel from palm oil in Malaysia, coconut oil in the Philippines and jatropha in Mali and Ghana.

Possessing alternative fuel resources and lacking oil reserves, however, are only part of the picture. The economic advantage of local sources is expressed most accurately in the price competitiveness of alternative fuels relative to conventional gasoline and diesel. Prices may depend on local innovations and conditions that are not always readily apparent or transferable. The use of relatively inexpensive hydroelectricity during non-peak hours to power three-wheeled vehicles in Nepal, for example, has enhanced the cost-effectiveness of that programme, as have the particularly productive soils and climatic conditions for efficient sugarcane and ethanol production in Brazil. Also, even if a country possesses oil reserves, a lack of refining capacity may make alternatives more economically attractive than oil. While Iran, for example, has significant crude oil reserves, it lacks refining capacity, making its natural gas more competitive with imported gasoline.

The price advantage of alternative fuels may fluctuate over time depending on world prices for oil and the alternative fuel in question. Fluctuations in world sugar and oil prices, for example have largely determined the path of the Brazilian ethanol programme, which since 1975 has experienced a series of peaks and valleys that mirror international oil prices. Prompted originally by high oil prices and low sugar prices, the Proálcool programme was successful in adding high-ethanol blends in the early 1970s and then hydrated/“neat” ethanol (typically 96 per cent ethanol and 4 per cent water) vehicles after the second oil crisis. By 1984 the number of cars running on pure hydrated alcohol reached 17 per cent of the country’s fleet, and by the late 1980s neat ethanol was used in over a quarter of the vehicle fleet: 3–4 million vehicles consuming nearly 10 billion litres per year. With the drop in world oil prices in the late 1980s, however, ethanol prices and related subsidies quickly lost

their advantage and the programme eventually collapsed, only to be revived again with the higher oil prices at the end of the 1990s. Recent revival of the market has been accompanied by the introduction of flex-fuel vehicles in Brazil that can run on any mixed proportion of gasoline or ethanol.

### *Supportive pricing policy and political commitment*

Policy support is another factor determining the market development of alternative fuels in transport. Policy support and public leadership involve research and development support, pricing support and regulations, overall coordination, codes and standards development, raising public awareness and political and symbolic leadership for the market. In some cases governments have played more interventionist roles in promoting alternative fuels than in others. Delhi's introduction of natural gas vehicles was prompted, for example, by a mandate from the Supreme Court of India in 1998 to replace the city's bus fleet, three-wheelers and taxis with gas and outfit the city with refilling stations. CNG sales subsequently increased dramatically from 0.99 lakh kg per day in March 2001 to 6.5 lakh kg per day in January 2003, and Delhi now has one of the largest CNG bus fleets in the world with 7,400 buses, 4,000 minibuses and 45,000 three-wheelers. Similarly, the Ministry of Petroleum in Egypt approved a set of companies which were given specific mandates and targets for vehicle conversion centres and filling stations.

All programmes have supportive fuel pricing, through either liberated pricing policies, tax exemptions or controlled prices that benefit alternative fuels, as well as incentives or tax breaks for new vehicles, vehicle conversions, refuelling infrastructure or production facilities. Table 5.7 shows the relative price advantage of natural gas in selected countries in 1998.

Table 5.7 Comparison of retail prices for fuels in selected countries, 1998 (US\$ per litre or equivalent)

Country	Premium petrol	Diesel	CNG
Argentina	0.96	0.44	0.30
Bolivia	0.44	0.43	0.22
Brazil	0.76	0.63	0.34
Mexico	0.45	0.32	0.25
Colombia	1.60	1.20	0.64
Egypt	0.15	–	0.075

Source: IANGV (2005).

*History of related innovation*

Alternative transport fuel markets are typically built on the legacy of existing industries and other fuel applications. LPG and natural gas are typically used as domestic or industrial power sources, for example, before they are used in transport. Pakistan, one of the world's most gas-dependent economies, started to use natural gas as early as the 1950s and now has a well-developed and integrated infrastructure (approximately 50,000 km of distribution and service lines). While possessing one of the world's largest natural gas vehicle programmes, Pakistan consumes only a small portion of its gas in transport. In 2003 45 per cent of natural gas consumption went to power, 18 per cent to fertilizer, 18 per cent to general industry and 2 per cent to transport (HDIP, 2004). Similarly, Mexico's use of LPG has followed the refining sector's development in that country, and the recent surge of natural gas vehicles in Chinese cities has followed the construction of the west-east gas pipeline network, constructed to bring natural gas from western China and Mongolia to the industrial centres on the east coast.

Ethanol and biofuel transport programmes typically redirect existing industrial production to the transport sector. The development of the Brazilian ethanol programme was built on the infrastructure and knowledge base that had been developed since the country's inception. In recent years sugar distilleries in the country have become highly productive ethanol producers. Table 5.8 shows the productivity gains in different

Table 5.8 Productivity gains during Brazilian ethanol programme, 1975–2004

Ethanol distillery process	Circa 1975	2004
Crushing capacity (tonnes of cane/day)	5,500	13,000
Fermentation time (hours)	24	4–6
Beer alcohol content (OGL)	7.5	10.0
Extraction yield (% sugar)	93	97
Fermentation yield (%)	80	91
Distillation yield (%)	98	99.5
Total yield (litres hydrated alcohol/tonne cane)	66	86
Total steam consumption (kg/tonne cane)	600	380
Steam consumption – hydrated (kg/litre)	3.4	2.0
Steam consumption – anhydrous (kg/litre)	4.5	2.8
Boiler – efficiency (% PCI)	66	87
Boiler – pressure (bar)/temperature (°C)	21/300	85/530
Surplus bagasse (%)	Up to 8	Up to 78
Biomethane from stillage (Nm <sub>3</sub> /litre alc)	–	0.1
Stillage production (l stillage/l alcohol)	13	0.8

Source: La Rovere (2005).

manufacturing capacities of Brazil's leading ethanol-distillery-equipment manufacturer (commanding approximately 80 per cent of market share) from 1975.

South Africa, which is starting to supply the transport sector with ethanol as a lead replacement for gasoline, is sourcing ethanol from existing production, which is mainly for industrial and pharmaceutical use. Similarly India, also a large producer of ethanol for non-fuel sectors (industrial, beverage and pharmaceutical), has begun to market ethanol-blended gasoline.

### *Supportive social attitudes and perceptions*

Alternative fuels are also typically viewed as key solutions to pressing social problems that are frequently related to one or more of the "drivers" mentioned above. Urban air pollution is often a key driver of alternative fuels in developing countries due to its magnitude and visibility and the degree of public exposure to the problem. The introduction of electric three-wheelers in Nepal was accomplished during a period of intense objection to visible air pollution from three-wheeled diesel vehicles, for example. The anti-diesel three-wheeler movement among NGOs, the tourism sector and others in Kathmandu peaked in early 1999 and the vehicles were banned, making way for the alternative technology. Urban air pollution was also the driver of the gas conversions in Delhi as well as LPG taxi conversions in Bangkok and other Asian cities. Pressure to improve air quality in Beijing and Shanghai in time for the upcoming world exposition and Olympics has driven natural gas vehicle programmes in those cities. Energy security and balance-of-payment concerns were the chief drivers in Brazil's ethanol programme, although climate change and the market mechanisms of the Kyoto Protocol have more recently drawn attention there, and industrial development and exports are key drivers behind emergent biofuel production in Ghana, Peru, Costa Rica, India and China. Industrial leadership and export potential are major drivers in Argentina.

## Conclusions

It is important to put alternative fuels and hydrogen into context in policymaking. The policies that drive hydrogen fall under goals relating to air pollution, climate change, oil dependency, industrial development and transportation. These goals, on their own, can be approached with a range of solutions, some of which are directly related to vehicle and fuel technology – the introduction of alternative fuels, for example – and

some of which are not, such as better urban transport planning. Some of these changes, moreover, respond to immediate and pressing manifestations of these goals, such as the need for domestic refining capacity for oil exporters, while others address longer-term implications, for example the need to develop a substitute for oil.

In terms of alternative transport fuels, developing countries have some of the largest and most successful alternative fuel programmes in the world. At present natural gas is used in a number of developing countries, as noted above. Brazil dominates global biofuel production, but other developing countries are investing in biofuels in the face of higher oil prices. There are also smaller pockets of LPG and electricity use in developing countries.

Experience shows that alternative fuels tend to be taken up in a manner that depends on a range of local conditions related to energy resources, policy leadership, social concerns and industrial experience. There is no reason to believe that the uptake of hydrogen will be much different, particularly since hydrogen is likely to be produced in a decentralized fashion, through different techniques and from various feedstocks available from country to country – an approach that is markedly different from today's more centralized and uniform gasoline and diesel production processes.

Based on these lessons, those countries, including developing countries, that are not at the forefront of hydrogen research and experimentation should monitor the latest developments closely and plan engagement in the hydrogen economy on the basis of a clear assessment of policy priorities relating to transport and energy and a solid understanding of local energy, technological and social characteristics that are likely to shape the development of alternatives to oil in a given setting.

## Notes

1. Major sources of nitrogen dioxide ( $\text{NO}_2$ ) are high-temperature combustion processes, such as those occurring in automobiles and power plant. Nitrogen oxides generally ( $\text{NO}_x$ ) also react with volatile organic compounds in the presence of heat and sunlight to create ground-level ozone (the main ingredient in smog), which can cause harmful respiratory effects including aggravating asthma and decreased lung function.
2. See chapter 12 for a discussion of the situation in Malaysia.
3. See chapter 16 for the Nigerian case.
4. There is now extensive evidence, accepted by the international scientific community, that the world is getting warmer, with an increase in global average surface temperature of about  $0.6^\circ\text{C}$  over the twentieth century. The atmospheric concentration of carbon dioxide has increased by 31 per cent since 1750 to levels that have not been exceeded during at least the past 420,000 years.

5. Greenhouse gas emissions include carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), halocarbon gases and some other synthetic compounds (e.g. perfluorocarbons).
6. In 2005 many Asian countries began reducing subsidies and letting consumer prices rise in the face of increasing world oil prices. Malaysia, Thailand and Indonesia, for example, have recently let prices rise, with near-100 per cent increases in Indonesia.
7. For a discussion of the Brazilian flex-fuel engines see chapter 6.
8. Energy-intensive bio-ethanol production from corn in the United States, for example, results in almost no CO<sub>2</sub> reductions, while some of the pilot plants in Europe using cellulosic feedstocks see up to 100 per cent improvement over gasoline (International Energy Agency, 2004b).

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## The ethanol and biodiesel programmes in Brazil

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### Introduction

Since the beginning of civilization, human ingenuity has been used to increase the efficiency of work and reduce physical human effort. Applications in energy technology have enabled achievements that otherwise would have been impossible. Societies that have had access to energy resources and the knowledge to exploit them have tended to enjoy significant benefits and improved standards of living.

Society's demand for energy, however, is constantly growing as a consequence of technological development and the improvement of living conditions. The average energy consumption of human beings has grown enormously, from the initial value of 2,000 kcal/day that characterized primitive man 1 million years ago to a modern average of 250,000 kcal/day per capita (the United States in 1970) (fig. 6.1). It is important to stress, however, that there is an enormous difference in the energy consumption when industrialized countries (25 per cent of the world population) are compared with the rest of the world. The United States, with just 6 per cent of the population, accounts for 35 per cent of the energy consumed in the world. This difference is reflected in the average per capita world energy consumption, reaching in 1998 the value of 18,000 kcal, or 1.79 TEP (tonne equivalent of petroleum) (Goldemberg and Villanueva, 2003). Modern society, however, relies heavily on an adequate supply of energy: at the end of the nineteenth century human effort

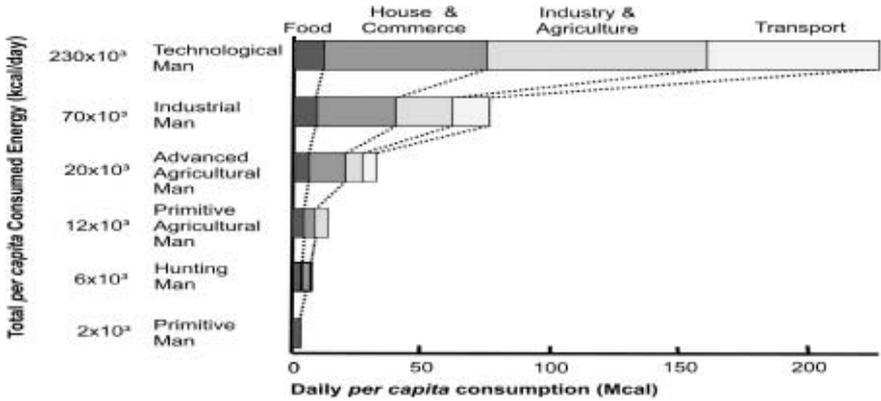


Figure 6.1 Per capita energy consumption over time  
 Source: Goldemberg and Villanueva (2003).

constituted 94 per cent of all industrial work in the United States; today it represents only 8 per cent (Lomborg, 2002).

A steady growth in world population has taken place in tandem with ever-increasing per capita energy consumption. Population, moreover, has grown geometrically in the last 1,000 years, placing additional pressure on energy resources. To satisfy the ever-increasing demand, humanity has made use of different energy sources, and the relative importance of these resources has differed between industrialized and developing countries. In 1988, for example, 37 per cent of the energy consumed in industrialized countries came from petroleum, 25 per cent from gas, 19 per cent from coal, 9 per cent from nuclear energy and only 10 per cent from renewable energies such as hydro and biomass. In contrast, although petroleum accounted for 33 per cent of energy resources in the developing countries, renewables such as biomass (22 per cent) and hydropower (7 per cent) provided 29 per cent of their energy sources (Goldemberg and Villanueva, 2003).

The great increase in fossil-fuel energy consumption observed mainly over the last century, along with increasing petroleum prices, has forced several countries to seek alternative energy sources in the last 30 years, as well as to improve their efficiency in energy consumption.

OECD countries account for 80 per cent of the world's economic activity, with annual energy consumption above 300 exajoules (EJ). Such countries are highly dependent on petroleum imports, and are responsible for 63 per cent of total primary energy consumption. It has been estimated that in 2100 this consumption will range from 500 to 2,700 EJ/year.

Renewable sources such as solar and biomass will likely play a central role in meeting future demand, with a lesser role for other renewables such as hydro, tidal and geothermal energy. The current use of renewable energy in the world amounts to an estimated value of 56 EJ/year (including 38 EJ/year coming from traditional biomass, like firewood). This is equivalent to 14 per cent of the world's consumption of primary energy.

Between 1970 and 1990 about 800 million people benefited from rural electrification programmes, mostly in China. In spite of this monumental effort, the number of people without electricity access remains the same in absolute terms today – around 2 billion (Goldemberg, 2002). The development and improvement of modern biomass technologies for electrification, as well as for cleaner energy supply in all sectors, including transportation, are of fundamental importance for improving the standard of living for excluded populations. Modern biomass also enables the substitution of the traditional use of biomass (firewood for cooking and performing other rural tasks) by more efficient forms of biomass conversion.

By 2004 renewable energies had come to constitute 43 per cent of total primary energy consumption in Brazil. Unlike other developing countries, where the burning of firewood is intensively used as an energy source, Brazil relies on a huge agro-industrial park for ethanol production from sugarcane. The country is the world leader in the production and consumption of renewable energy from biomass, and often serves as an example for other countries in using local biomass resources to achieve the Millennium Development Goals and help mitigate greenhouse gas (GHG) emissions and the impact of climate change.

Therefore, although hydrogen seems to be the most promising energy source in the long term for the transport industry, for developing countries biofuels present a more feasible alternative in the short term, as the Brazilian experience demonstrates. This chapter intends to show, in light of this experience, how developing countries can develop alternative sources of energy and take advantage of these to improve their living conditions.

## The Brazilian alcohol programme (Proálcool)

The 1970s were a time of military dictatorship in Brazil. The government was closely associated with multinational capital as well as with large Brazilian agrarian and industrial capital. The decade saw several international economic crises. Financial deficits grew sharply as a function of rising imported petroleum prices, and an appreciable rise in external debt occurred as a consequence of increasing international interest rates.

Another component of the deficit was the historically low exporting capacity of the country, in association with the accelerated expansion in capital goods and intermediate imports needed to achieve the II National Development Plan of the Geisel government (1974–1978). By that time the close relationship of the government to international financial capital had enabled the country to secure the financing of international private banks in order to pay for the copious state enterprise investments demanded by the development plan. Rising interest rates, and the subsequent financial burden on the country, would be one of the central components of the deep crises Brazil confronted from 1981 to 1984.

The petroleum crises, furthermore, had a sizeable impact on the country's financial health. Although the state petroleum company (Petrobrás) had initiated its activities in 1954 and there was considerable investment in oil exploration and refining, more than 80 per cent of the petroleum used at that time was imported (fig. 6.2). Regarding electricity generation, it was as it is today: predominantly hydroelectric. Again, many of the hydroelectric plants (including the world's largest, Itaipú) were built in the 1970s. The nuclear agreement with Germany, which led to the construction of several nuclear electricity plants, also dates back to this period. By the middle of the 1970s overall Brazilian dependence on external energy sources was around 45 per cent, as shown in figure 6.2.

The search for alternative fuels in Brazil can be dated back to the 1920s, when the Instituto Nacional de Tecnologia (INT) carried out experiments using biofuels in internal-combustion engines. It was not until the 1970s, however, that the implementation of alternative fuels was

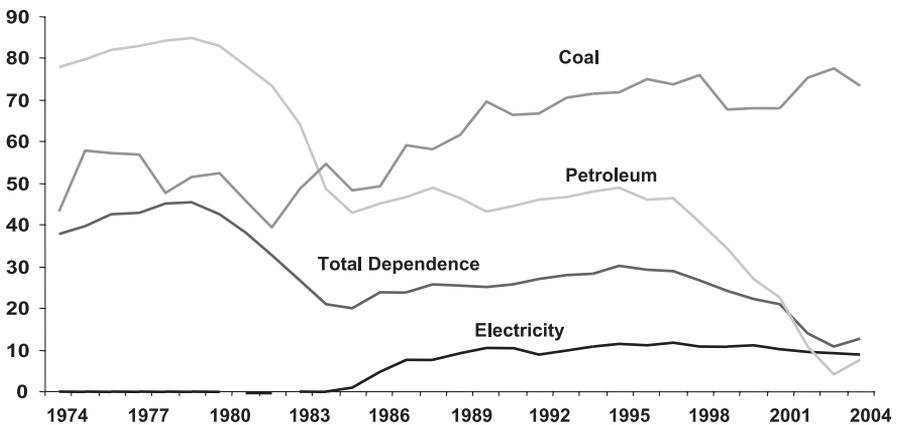


Figure 6.2 Brazilian external energy dependence to the year 2004 (%)

Source: Ministry of Mining and Energy (2005).

seriously considered, primarily as a means of alleviating the country's energy dependence. This motivation, along with the low price of sugar in the international market and the strong pressure and political power of the sugarcane producers, enabled the elaboration and implementation of the Brazilian alcohol programme (Proálcool<sup>1</sup>).

Proálcool also benefited from a previous rural and industrial productive infrastructure, sustained by extensive rural property and industrial plants in the north-east and south-east regions of the country. This industrial oligarchy had been very influential since colonial times. The Brazilian alcohol programme was therefore initially dominated by sugarcane monoculture and concentrated in two regions of the country (north-east and south-east). Only recently has it been expanded to the centre-west region.

The technologies to produce sugar and alcohol were developed in colonial times, combining large land properties and slave-based production, as well as mills for sugar manufacturing and sugar exportation from the north-east. After the 1930s the old sugar mills were transformed into modern industrial plants. In the south-east and centre-west modern production methods and technologies were used but old practices were preserved, namely the concentration of land and the use of cheap labour to remain competitive in the internal and external markets.

The USA-Cuban crises (1961) gave new vitality to the production and export of sugar from Brazil. With the petroleum crises and the decrease in sugar prices in the international market, the implementation of Proálcool promoted the technological diversification of the sugar-alcohol production chain in each of its components and in its organizational infrastructure. During the 1990s some large agricultural enterprises intensified innovation in land treatment, planting, handling and harvesting, but low-wage labour remained a key component in the sugar industry. Since colonial times people employed in the sugarcane plantations, the "cane-cutters", have been subjected to precarious labour conditions. From the 1990s cane-cutters were subcontracted by means of so-called "cooperative-cats",<sup>2</sup> maintaining, if not worsening, the precarious conditions. The technological improvements, the subcontracting of the cane-cutters and the concentration of capital in four big sugarcane agro-industrial enterprises, which accounted for more than 90 per cent of the sugarcane purchase in São Paulo state or 60 per cent of national production, caused the unemployment of thousands of workers (Silva, 2004). In São Paulo state there are approximately 40,000 cane-cutters. The increasing area planted to sugarcane forces them to improve their productivity constantly, deteriorating their working conditions even more (Toledo, 2005). Other authors, however, paint a more positive picture (Nastari, Macedo and Szwarc, 2005). Figure 6.3 shows the ratio of jobs per generated energy and the investment per steady job from the sugarcane/

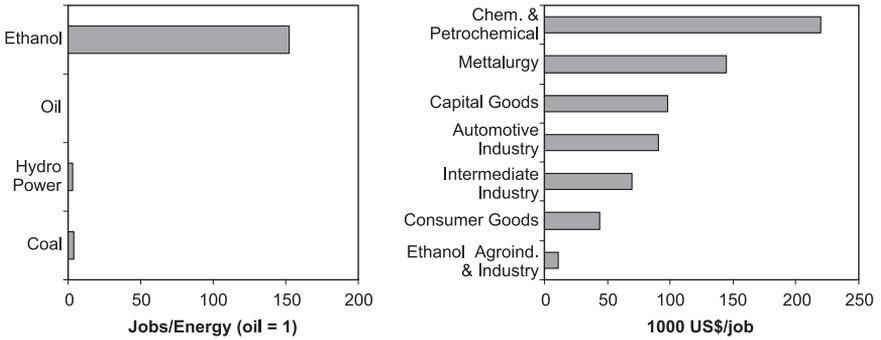


Figure 6.3 Employment per generated energy and investment per steady job in sugarcane and alcohol (Proálcool, 1980–1984) and other economic activities  
*Source:* Goldemberg (2002).

alcohol sector and other economic activities. Sugarcane plantations are spread across more than 5.6 million ha, employing 5 million people overall. Direct jobs account for 1.2 million: 511,000 people employed in sugarcane production, where manual harvesting accounts for 80 per cent of the total production of sugarcane, and the remainder are involved in sugar and ethanol production. This represents about 6 per cent of Brazilian jobs in agro-business (Viana Filha, 2005).

It is important to emphasize, therefore, that Proálcool was born within the context of technological and productive arrangements that were already available for sugar and alcohol production and were associated with an organized and strong political lobby. This powerful combination of factors made it possible to overcome the opposition of the petroleum companies as well as the gasoline-car-manufacturing industries during the first phase of Proálcool.

The economic, financial and political conditions in Brazil in the early years of the twenty-first century differed notably from those of the 1970s. Once again there is a significant increase in petroleum prices, but this time with much more political tension arising from anti-Americanism and terrorism in the oil-producing regions. The Brazilian trade balance shows rising surpluses, but the services balance (especially the financial one) is in large deficit and the state financial deficit is even greater, as a consequence of the large public debt and high interest rates (around 19.5 per cent in October 2005). Brazil's investment capacity is highly reduced, limiting the reach of any policy for infrastructure or social improvement, severely obstructing economic growth and leading to unemployment, violence and serious socio-economic problems. Added to this, the state has been largely adopting neo-liberal planning and investment

policies imposed by the IMF and World Bank and carried out in association with internal Brazilian oligarchies.

From the point of view of the energy balance, the Brazilian situation is much better now, as seen in figure 6.2, considering that the country has achieved self-sufficiency in oil production/consumption. A new source of fuel and energy is now available in natural gas imported from Bolivia. Political uncertainties, however, put in doubt the reliability of these imports. A huge reserve of gas has been found in Brazil, in the Santos Basin, and should be available for consumption in a few years.

The sugarcane sector in Brazil is in a period of great buoyancy. The steady increase in the international price of oil, the Kyoto Protocol, the EU targets to reduce greenhouse gases and the global mass production of flex-fuel vehicles are powerful incentives for this industry. Furthermore, there has been considerable technological advance over the past 30 years, which has reduced the cost of ethanol production by two-thirds – as illustrated in figure 6.4 showing the ethanol learning curve.

Currently, more than 350 million tonnes of sugarcane are produced and processed annually by the sugarcane sector in Brazil. More than 50 per cent of this amount is used in ethanol production. Six thousand litres of ethanol are produced per hectare per year on average. There are more than 500 varieties of sugarcane available, although only 20 of these account for 80 per cent of the market (Hassuani, Leal and Macedo, 2005;

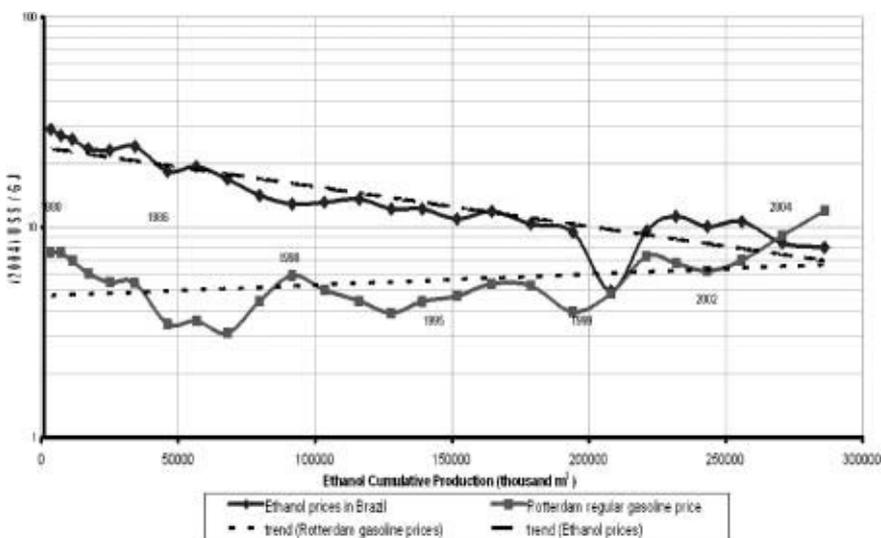


Figure 6.4 Ethanol learning curve

Source: Nastari, Macedo and Szwarc (2005).

Leite, 2005b). Of the overall amount of ethanol produced from the 2003–2004 sugarcane harvest in Brazil, 12.5 billion litres were consumed by the internal market and 0.7 billion litres were exported. Although the amount destined for the external market is still modest, it grew from 0.4 per cent of the 2002–2003 harvest to 2.6 per cent in 2003–2004. In 2004 a total area of 5.34 million ha was designated for sugarcane plantations associated with sugar and alcohol production in Brazil. This represented less than 10 per cent of the total crop area (60.4 million ha) and a small fraction of the estimated 300–320 million ha of arable land in the country (Nastari, Macedo and Szwarc, 2005).

The low efficiency of photosynthesis, however, is a great obstacle to the widespread use of biofuels worldwide (Lomborg, 2002). If all the petroleum consumed in the world were to be substituted by biomass, a planted area equivalent to the entire Brazilian territory would be necessary. However, according to Leite (2005a), Brazil can increase its production of ethanol 10-fold utilizing only 30 per cent of the 90 million ha of arable land that can be used with low environmental impact. It must also be pointed out that the energy output from ethanol produced through fermentation of sugarcane juice is 700 per cent; in contrast, ethanol production from corn yields only 20 per cent more energy than is used to produce the alcohol. The US alcohol programme can thus be maintained only if government subsidies are allowed. Ethanol from sugarcane, on the other hand, can be competitive with gasoline without subsidies (Leite, 2005a, 2005b).

The sugarcane sector accounts for approximately 9 per cent of the overall Brazilian energy matrix. Hydroelectricity contributes 65 GW of the total 82 GW of electricity produced in Brazil on an annual basis. Co-generation of electricity from sugarcane bagasse had made steady progress in recent years, with new technologies for energy production from bagasse burning, waste gasification and gas turbines powered by bagasse gasification. Bagasse gas-turbine technologies have the potential to produce power six times more efficiently than traditional vapour systems (the use of modern gas-turbine technologies in all plants could contribute 30 per cent of the overall electricity generated nowadays in Brazil). This might help Brazil's effort to avoid energy shortages – assuming a modest 3 per cent annual growth in GDP takes place, by 2009 Brazil could face serious supply problems (Hassuani, Leal and Macedo, 2005). Sugarcane bagasse can also be used to produce ethanol and methanol. It is claimed that four times more methanol can be produced from sugarcane bagasse compared to ethanol produced from fermentation of sugarcane juice (Audi, 2005; Viana Filha, 2005).

The use of sugarcane waste and bagasse to generate energy could contribute to a 44 per cent reduction in GHGs originating from fossil fuels in

Brazil. If 50 per cent of the oil-based power capacity is substituted, an amount of US\$110 million/year in carbon credits could be generated (Hassuani, Leal and Macedo, 2005). The use of wastes, however, requires further technology improvements before it can be employed on a commercial scale.

Ethanol fuel use has resulted in a 50 per cent reduction of the gasoline that would have been consumed in Brazil since the end of the 1970s, representing an estimated 10 per cent reduction in GHG emissions by the country's automobile fleet. The foreign exchange savings are estimated as US\$50 billion (Goldemberg, 2002).

The use of ethanol fuel is environmentally advantageous as compared to gasoline, for a number of reasons.

- It produces low emissions, giving a drastic reduction in atmospheric CO<sub>2</sub>. Life-cycle assessments showed that a fivefold reduction in CO<sub>2</sub> could be achieved when ethanol is used in place of fossil fuels (IPCC, 2001).
- It presents lower toxicity and is biodegradable.
- It contains oxygen and therefore burns more efficiently, resulting in "lean" combustion and less exhaust emissions, mainly CO.
- It does not emit sulphur oxides (SO<sub>x</sub>).
- It reduces emissions of "photochemical smog" precursors due to its lower photochemical reactivity.
- It does not emit particulates.
- It is less volatile than gasoline, causing less evaporative emissions during storage, transportation and handling.

Ethanol also has a higher octane number than gasoline – in fact it has been successfully used as an effective "octane enhancer" in place of other expensive octane additives such as MTBE and the highly toxic TEL.

Ethanol cars produce more aldehydes than gasoline cars. However, it must be realized that the aldehydes produced by ethanol are the typically much less toxic acetaldehyde, compared to the very toxic and carcinogenic formaldehyde associated with methanol. Regarding NO<sub>x</sub> emissions, there is little difference between ethanol and gasoline cars. On the other hand, gasohol (gasoline plus ethanol) cars tend to produce higher NO<sub>x</sub> emissions – although some authors claim that if careful engine calibration is performed, the NO<sub>x</sub> emissions of ethanol, gasoline and gasohol cars do not differ appreciably. It has been also claimed that the amount of NO<sub>x</sub> emissions depends on the proportion of ethanol blended in gasoline, the characteristics of the base gasoline, the response of the vehicle to the fuel and the traffic conditions (Nastari, Macedo and Szwarc, 2005; CETESB, 2003).

In 2004 there were 1.35 million flex-fuel vehicles running in Brazil, out of a total of 22 million light vehicles (ANFAVEA, 2004). According to

the CETESB (Coelho, 2005), vehicle emissions from flex-fuel automobiles show similar figures when compared to hydrated ethanol<sup>3</sup> or gasohol cars.

Regarding emissions in sugarcane production, the burning of sugarcane straw is a common practice in manual harvesting. The ongoing automation of harvest processes in some mills may reduce these emissions (mainly NO<sub>x</sub> and methane); however, this may cause the loss of many jobs. Nonetheless, São Paulo's state environmental legislation bans straw burning from 2020.

There is conflicting information about the use of stillage for fertirrigation<sup>4</sup> in sugarcane plantations. Some authors claim this co-adjuvant has many beneficial effects, including an increase in soil potassium concentration, and also saves on fertilizer usage and therefore on fossil energy used by fertilizer industries (Nastari, Macedo and Szwarc, 2005). Others, however, claim that stillage application in sugarcane plantations causes soil erosion (Couto, 2000).

## The Brazilian biodiesel programme

Although the development of alternative fuels in Brazil started early in the last century, support for biodiesel<sup>5</sup> research only began in the 1960s. The initial motivation for this support was related to the strategic and national security considerations of the military government, concerned with isolated communities, mainly in frontiers regions, where the supply of diesel fuel was difficult for logistical reasons. It was thus of interest to produce the fuel locally. From the 1970s there was also a need to find alternatives to expensive petroleum.

Thus, a few years after the start of Proálcool, the government developed another ambitious programme, the so-called Prodieisel, which aimed to set up the agro-industrial infrastructure to produce what is known today as biodiesel.<sup>6</sup> Prodieisel was in principle easier to implement than Proálcool, since use of biodiesel did not require engine modification, as is the case with alcohol. Much research was carried out during this period, resulting in the first international biodiesel patent by Brazilian scientists (Parente, 1980), among other publications. Many tests were carried out employing pure biodiesel or biodiesel-diesel mixtures; biodiesel was even tested in airplane turbines at that time. However, it could not compete with cheaper diesel oil and the Prodieisel programme did not proceed further.

This situation remained unchanged up to the 1990s, when European countries, followed by many others and motivated mainly by concern

over environmental impacts and the supply uncertainty of petroleum, began introducing biodiesel. In 2002 the Brazilian Ministry of Science and Technology set up a network of institutions to study the production and use of biodiesel made from the transesterification reaction of soyabean oil with ethanol. In 2003 an interministerial committee for biodiesel was established under the new government which took office that January. This committee was charged with analysing the possibility of the production and use of biodiesel in Brazil, and it undertook a series of public hearings across the country with public and private institutions related to the biodiesel production chain (research, performance tests, industrial production, agriculture and so on), as well as federal and state parliaments. The main conclusions of the hearings were as follows (Rodrigues, 2005).

- Biodiesel can contribute favourably to many fundamental problems in Brazil by generating jobs and income (social inclusion); reducing environmental pollutants, resulting in reduced costs for the public health system; mitigating regional inequalities; and reducing petroleum imports.
- Biodiesel is already available in many industrialized countries. The common motivation for its use in those countries relates to environmental pollution and the reduction of “petrodependence”.
- Brazil has made advances in biodiesel technology since the 1970s. However, those advances were discrete and not harmonized. Brazil can produce biodiesel through many technological routes and raw materials, which can be adjusted to the regional diversity in the country so that all regions can be involved in biodiesel production. This approach could reduce regional inequities.

Based on these conclusions, the committee elaborated the following recommendations.

- Immediate inclusion of biodiesel in the official agenda of the government to send a positive signal to the biodiesel industry.
- Social inclusion and reduction of regional inequalities should be the orienting principle of the National Programme for the Production and Use of Biodiesel.
- To grant official authorization for use of biodiesel in Brazil. The committee considered this an important step to make the country a possible beneficiary of the carbon credit market (as in the clean development mechanism of the Kyoto Protocol).
- To carry out recognized and certified tests (in vehicular and stationary applications) and R&D activities in partnership with the automobile industry, the Brazilian states and other countries.
- To perform technical studies with economically viable raw material and agricultural production at the national level.

- To formulate norms, regulations and quality standards for biodiesel according to its different uses.
- To implement public policies (for financing, technical assistance, rural extension and research grants) aimed at increasing efficiency in biodiesel production.
- To avoid subsidies for biodiesel and its productive chain, in order to circumvent distortions over time, and instead to allow fiscal incentives to achieve economic, social and environmental sustainability for the biodiesel production chain.

In the overall implementation of these recommendations, an inter-ministerial executive commission directly subordinate to the presidency was created. A managing group subordinate to the Ministry of Mining and Energy was also established. In 2004 the group presented and obtained approval for a working plan to implement biodiesel in Brazil. Since then, many laws and regulations have been adopted to put this plan in practice.

There are some aspects of the Brazilian biodiesel legislation that should be highlighted in order to show how this programme differs from those in other countries and from the earlier Proálcool programme. Law 11116 (of May 2005) and Decree 5297<sup>7</sup> (6 December 2004) exempt biodiesel producers from paying the IPI tax and regulate reductions for them in the PIS/PASEP and COFINS taxes.<sup>8</sup> However, after providing an across-the-board 0.6763 aliquot reduction in PIS/PASEP and COFINS taxes, this legislation goes further, to allow an incremental reduction if the raw materials are purchased from family agriculture<sup>9</sup> and offering differential incentives depending upon the type of raw material input used and the region in which it is grown. The greatest incentives accrue to biodiesel made from palm or castor oil produced in the north, north-east or semi-arid regions of the country and bought from family agriculture. Under such conditions there is no need to pay PIS/PASEP or COFINS – an incentive equivalent to approximately US\$90.0/m<sup>3</sup> (R\$218.00/m<sup>3</sup>) of biofuel.

Agrarian Development Ministry Normative Instruction No. 2 (30 September 2005) specifies the norms for biodiesel production project financing, with special financing conditions for projects that promote social inclusion of family farmers as raw material suppliers. Producers can be awarded the so-called “social fuel stamp”; to be eligible for this, the biodiesel producer must meet certain conditions.

- A minimum quantity of the total annual amount of raw material to produce biodiesel must be bought from family farmers: at least 50 per cent in the north-east region of the country; 30 per cent in the south and south-east regions; and 10 per cent in the north and centre-west regions.
- Technical assistance must be provided to family farmers.

From 13 January 2005, Law 11097 introduced biodiesel in the energy matrix of Brazil, fixing a mandatory percentage of 5 per cent biodiesel in diesel oil (B5) from 2013 and a 2 per cent mixture (B2) from 2008. Finally, Resolution No. 3 (23 September 2005) of the National Council for Energy Policy obliges oil producers and importers as of 1 January 2006 to purchase first all the biodiesel that is available from companies or associations awarded with the social fuel stamp, and only then to purchase biodiesel from other producers. This biodiesel will be sold through public auctions held by the National Agency for Petrol and Biofuels (ANP). It would appear that with this biodiesel programme the government intends to avoid the mistakes observed in Proálcool, notably the concentration of production in just a few hands and in only in some regions.

Table 6.1 shows the regions of Brazil, the main oil plants they produce, the industry installed oil extraction capacity and the demand for biodiesel production if a B5 mixture of biodiesel and diesel oil is required. Very few countries have the same diversity of biodiesel sources available to Brazil. Currently, the country produces four times more vegetable oil than the amount necessary for the implementation of a B5 mixture in the national fleet. Much of this is based on edible soyabean oil. However, it is important to note that Brazil uses a relatively small amount of its land for agriculture and much land is available without the need for deforestation. New technologies for cattle raising and mixed farming/husbandry, for example, may allow for a 40 per cent reduction in required pasture land. There are also degraded lands that can be recovered for agriculture. Brazil uses 7 per cent of its land for agriculture and 35 per cent for pasture; forest occupies 55 per cent of the territory. According to EMBRAPA (the leading Brazilian agricultural research company), there are 90 million hectares of land available for agriculture

Table 6.1 Regional potential, demand and industrial installed capacity for biodiesel production in Brazil

Region	Diesel consumed (000)	Biodiesel demand (B5)	Oil industry installed capacity (t.10 <sup>3</sup> )	Main oil plants
South	6,836	342	3,400	1, 2, 4, 8, 9, 10
Southeast	15,028	751	1,300	1, 3, 8, 4, 9, 10
Center west	3,899	195	1,700	1, 3, 8, 4, 5, 9
Northeast	5,120	256	400	6, 1, 3, 5, 8, 7, 9, 10
North	2,717	136	150	5, 6, 1, 9
Total	33,600	1,680	6,950	

Key: (1) Soya (2) Colza (3) Castor (4) Sunflower (5) Palm (6) Feather palm (7) Coconut (8) Cotton (9) Animal fat (10) Fish oil

Source: Adapted from ANP/ABIOVE.

Table 6.2 Average production from various oil plants

Oil plant	Average production (litres/hectare)
Palm	6,000
Piqui ( <i>Caryocar brasiliense</i> )	3,200
Peanut	2,100
Castor	2,000
Babassu (feather palm)	1,600
Sunflower seed	800
Soya	400
Cotton	280
Corn	160

Source: Jesus (2005).

in Brazil that could be used with negligible environmental impact (Nastari, Macedo and Szwarc, 2005).

Table 6.2 shows the oil productivity per hectare of some of the main oil plants available in Brazil. The palm tree is by far the most productive. Although it takes four to five years to start production, it has the advantage of being a permanent culture that lasts for about 100 years. Palm, babassu and piqui (*Caryocar brasiliense* Camb) are all very productive permanent cultures; however, only palm was given fiscal incentives for biodiesel production under the legislation. It is important to mention that the palm tree is very common in the Amazon. In this remote region one could consume four litres of diesel oil for every one litre of this oil delivered to isolated communities. According to specialists, biodiesel from castor oil generates 400 per cent more energy than is used to produce it; and in the case of palm oil the ratio is even higher, amounting to 500 per cent (Canzian, 2005).

Concerning temporary cultures, peanut is the most productive in terms of the ratio of the extracted oil per planted area, followed closely by the castor-oil plant. Castor oil is among those crops granted fiscal incentives for biodiesel production in Brazil, as mentioned above. This temporary culture is important because it does not require expensive tools or sophisticated technological assistance, and is therefore appropriate for small family agriculture businesses. However, some specialists criticize as excessive the government's focus on biodiesel from castor oil, claiming that it is more expensive to produce because of its longer reaction time, has a high viscosity, lower calorific power and a lower cetane number, and consequently has lower potency as compared, for example, with other vegetable or animal oils.

The use of soyabean and cotton oils to produce biodiesel, although not favoured when one considers the low oil yield per hectare, is important to consider because of the large volume, organized productive chain and technological capacity the country has for these crops. Brazil is a world leader in productivity in these crops. In the case of cotton, it is worth mentioning that oil from cottonseed is produced as a by-product in textile manufacturing. Many farmers from the centre-west region of Brazil are interested in producing biodiesel from cottonseed oil, since they have large quantities of cottonseed and cannot get good prices for it in the region. Soya accounts for 98 per cent of grain production in Brazil.

Furthermore, Brazil is the world's largest beef-cattle and chicken producer and is a significant producer of pork meat. Mato Grosso state alone produces 22 million cattle (10 per cent of the national production), illustrating the large potential of biodiesel derived from animal fats. Producing biodiesel from animal fat could also be important from the environmental point of view by eliminating the dumping of these fats, which are generally considered a waste in the meat production process. The environmental service provided by finding a noble use for these wastes, in addition to the savings in butcher plants that this can provide, is worthy of notice. Unfortunately, Brazilian legislation does not provide incentives for biodiesel produced by this way.

Allowing the production of biodiesel from different raw materials, however, introduces a new complexity in production not seen anywhere else in the world. The different vegetable oils and animal fats yield biodiesel with diverse physicochemical characteristics, necessitating the development and adoption of a sophisticated quality control system. The ANP is responsible for monitoring the quality of biodiesel in Brazil, as well as aspects related to its production and distribution.<sup>10</sup> There are standard quality control methods for several types of biodiesel, but castor-oil biodiesel still requires an official method (the ANP adopted, provisionally, a method developed by Petrobrás).

Biodiesel can be produced by many different technological processes; the simplest and most widespread one makes use of vegetable oils and methanol in the presence of potassium or sodium hydroxide, in a chemical process called transesterification reaction. This process produces biodiesel in high yields with glycerine as a co-product, and offers advantages in terms of simplicity of production. Biodiesel from methanol is produced by using a toxic compound (methanol) originated mainly from non-renewable sources (petroleum); however, new technologies for methanol production from renewable sources are foreseeable in the near future.

As may be expected, biodiesel will be produced in Brazil mainly through the use of ethanol as the transesterification agent, building on the country's experience and market development with ethanol. Ethanol,

moreover, is a non-toxic biodegradable agent, as compared to methanol. But the transesterification reaction with ethanol presents some technical difficulties not encountered when methanol is employed. The reaction with ethanol requires high temperatures and produces an emulsion that causes problems during the purification process. Another problem is the lack of solubility of sodium hydroxide in ethanol. Although relatively satisfactory technological solutions have been found to overcome these difficulties, it is true that the conventional methanol-base-catalysed method is still simpler, cheaper and produces biodiesel generally in higher yields.

The use of a base to catalyse the reaction presents restrictions, regardless of the transesterification agent employed (methanol or ethanol). The vegetable oil or animal fat to be transesterified through these base-catalysed processes must be neutral. If there is any acidity in the oil, processing will form soaps, producing emulsions and making it difficult to purify the products. In addition, if the alcohol is not anhydrous the water present will prevent the reaction from proceeding smoothly, reducing the yield drastically.

To overcome these problems, researchers from the Pantanal Regional Environmental Programme, a joint initiative from the Federal University of Mato Grosso and the United Nations University (UFMT/UNU-PREP), have patented a new and very efficient solution (Dall'Oglio, Sousa and Garofalo, 2005). The transesterification reaction is carried out in the presence of microwave radiation instead of conventional heating processes. This allows the reaction to take place in the presence of an acid catalyst, overcoming the problems associated with the base-catalysed processes mentioned above. The reaction also proceeds smoothly when ethanol is used, and the presence of water is tolerated regardless of the transesterification agent employed.<sup>11</sup> This technology is being scaled up at the moment in order to establish the optimal conditions for the reaction to proceed in industrial plants.

In 2000 the use of fossil fuels accounted for about 9 gigatonnes of carbon dioxide emissions worldwide. It has been estimated that by 2030 CO<sub>2</sub> emissions from oil use will increase by 60 per cent, amounting to 15 gigatonnes (Haug, 2004).

The use of biodiesel,<sup>12</sup> as with ethanol, presents many environmental advantages. As a renewable biofuel, it contributes to the international effort to reduce GHGs. Compared to diesel oil, biodiesel produces 78 per cent fewer emissions of carbon dioxide (Holanda, 2004). It is virtually free from sulphur and therefore produces no sulphur dioxide emissions. Biodiesel is a very good lubricant, and can be used as an additive in diesel oil to replace sulphur, which in the past was used as lubricant in diesel despite its negative environmental impact. Currently, there is a great effort to produce diesel oil with low sulphur content, requiring lubricant

additives in order to avoid engine damage. As an oxygenated fuel, biodiesel burns more readily than diesel oil and thus reduces drastically the emissions of toxic carbon monoxide. The nitrogen oxide emissions of biodiesel, however, are slightly higher than diesel oil (Clery, 2001). Biodiesel engines show overall superior combustibility when compared to their diesel counterparts. This can be explained by the better cetane index (and therefore better combustibility) of the former.

According to the Swedish Environmental Protection Agency in a study considering new petrol and diesel-driven cars, there is an environmental cost equivalent to US\$0.10 per litre of petrol and US\$0.20 per litre of diesel arising from the vehicular use of fossil fuels. An annual saving of US\$100 million would be feasible for 1 million cars running with renewable fuel (e.g. ethanol, biodiesel) if a 25 per cent reduction of environmental hazards is assumed as a consequence of cleaner exhausts (Goldemberg, 2002).

Brazil's diesel consumption amounted to 35 million m<sup>3</sup>/year in 2004, with 5 million m<sup>3</sup> of imports. The use of a B2 blend, mandatory from 2008, will require the production of 800,000 m<sup>3</sup>/year (and a B5 blend will require 2 million m<sup>3</sup>/year). Although the country possesses advanced agricultural technology and extensive experience in the production and use of biofuels (e.g. ethanol), one cannot take for granted that this high quantity of biodiesel will be easily produced in the short term.<sup>13</sup>

Unlike Proálcool, the biodiesel programme was not preceded by earlier technological developments, except for the technology available for some crop production (e.g. soyabean and sugarcane), and a modern edible oil and ethanol industry. This lack of infrastructure could be considered the main bottleneck in the Brazilian biodiesel programme. There are also only a small number of reliable entrepreneurs dealing with equipment for the biodiesel industry. Some of these companies are the same as those producing equipment for the ethanol industry, and their competence in the biodiesel business is not yet proven.

Industry has tended to complain about the lack of financing despite government promises. In 2005 the Programme for Biodiesel Financial Support from the National Bank for Social and Economic Development (BNDES) was considering an amount of R\$450 million (US\$200 million) in loans. The bank claims that the reason for the delay in making loans is the tedious procedures required for environmental licences. The Bank of Brazil (BB) also has special facilities for the biodiesel business; in this case, the bank is interested in financing the whole production chain as a way to minimize risks. Another recurrent complaint concerns insufficient tributary incentives and the limitation of these incentives for palm and castor oil produced in the north and north-east regions of the country. It

should also be noted that government incentives for palm- and castor-oil production can lead to the undesirable predominance of monocultures in these regions. The deleterious effects of monocultures, namely the negative environmental impacts and the economic risks associated with dependence on a single product market, are well known and were experienced in Brazil when the country chose only sugarcane for the alcohol programme.

According to data provided by the Brazilian Association for Biodiesel (Abiodiesel), as of May 2005 there were eight biodiesel projects going on in Brazil with an overall production capacity of 444 million litres/year (this would account for half of the 800 million litres/year necessary to achieve the B2 blend).<sup>14</sup> Still, according to Abiodiesel, biodiesel production in Brazil using soyabean (as under government support provisions) will be profitable only if it is exported. Castor and palm oils, on the other hand, tend to have more attractive prices in the international market.

Proálcool, although a larger undertaking than the biodiesel programme, was implemented at a time when the investment capacity of the state was higher. Nowadays there is relatively little money for productive investment in infrastructure, although much more money is being spent in the development of new technologies for alcohol and biodiesel production. Most of Brazil's finances are driven by external and internal debt. During the 1970s economic news in Brazil was dominated by headlines related to production records in many industrial sectors and heavy government investment in infrastructure. In contrast, nowadays the stock market, dollar and euro exchange rates, the so-called "Brazil risk" and ever-increasing profits for the financial sector are the main topics.

The neo-liberal faith in market solutions is, unfortunately, dominating the political scenario in Brazil. This is clearly reflected in the formulation of the biodiesel programme, which is characterized by the absence of regulatory power – the key to the success of the alcohol programme. The authors strongly believe that a long-term strategy is the basic premise for the long-term success of a national renewable energy programme. This strategy should take into account all the programme parameters, e.g. the technological structure, the financing availability and the market and management strategies and policies. The lack of a long-term strategy has weakened the efficacy of incentives for developing industrial technologies, created uncertainty over the capacity of national industry to supply necessary capital investments and led to difficulties in defining a minimum price for biodiesel; all of which stand to undermine the programme seriously. Although it is likely that biodiesel will see international demand growth over the next 30–50 years, and despite the Brazilian legislation developed to provide a framework for biodiesel business in the

country, the success of the biodiesel programme cannot be taken for granted.

The lack of previous biodiesel production experience in the country and of methodologies for research on revenues and costs, as well as other issues, makes it difficult to estimate initial biodiesel prices in the Brazilian market. According to some specialists, the initial price could vary from two to three times the price of conventional diesel (it must be noted, however, that these estimates were made before the price of oil reached US\$70/barrel). Biodiesel produced from palm or castor oil and biodiesel certified with the social fuel stamp should be cheaper, according to current legislation.<sup>15</sup> Moreover, the market imposed by the legislation (B2 immediately and B5 from 2013) will create the conditions for economies of scale and lower prices in the future. Co-product sales (bran and glycerine) can also contribute to mitigate the price of biodiesel, increasing its competitiveness. Certainly, increasing petroleum prices favour the biodiesel programme goals in Brazil.

## Conclusion

Biofuels can make an important contribution to the achievement of the Millennium Development Goals as well as to the mitigation of climate change impacts by reducing greenhouse gas emissions. Improved air quality due to lower conventional emissions from biofuels can reduce public health expenses in many countries, especially developing countries, allowing this money to be applied in social programmes. Biofuel production can also lead to poverty reduction, generating new jobs and income in developing countries. Although the authors do not agree with the argument that there is a shortage of food in the world (hunger is caused by poor distribution of food and social inequities, and is not due to shortages in food production), it must be said that the use of land to produce biofuels must not compete with the use of land for food production. In this sense, Brazil occupies a very privileged position: it is the fifth-largest country in the world by territory size (850 million ha) and still has great availability of croplands. Sugarcane occupies 0.6 per cent of the territory, and it is estimated that the area eligible to support this kind of crop amounts to at least 12 per cent (Nastari, Macedo and Szwarc, 2005). Brazil also has the advantage of being the world's leading country in the production and use of biofuels: it was the first country to use ethanol in its vehicular fleet, and has more than 30 years of experience in the production and use of the ethanol biofuel.

In September 2005 the Rio de Janeiro stock market inaugurated the Clean Development Mechanism Project Stock. Seventy-four projects, with the potential to avoid annual emissions of 130 million tonnes of CO<sub>2</sub>, have been initially identified. This should place the country in a world-leading position in the CDM market (Oliveira, 2005).

The protocol on European targets for biofuels signed by EC countries for GHG emissions reduction and also the efforts to use sulphur-free diesel (biodiesel would be an excellent additive in this case, as noted above) present a great export opportunity for Brazil. However, it is too early to assume that the country can take full advantage of this situation. The biodiesel programme, although less challenging than its predecessor Proálcool, is only in its infancy and its success is yet to be seen. Nevertheless, this and other export possibilities are certainly a positive sign to other developing countries intending to implement biofuels in their energy matrix. The globalization of the biofuel market is in the interest of Brazil, since it will provide stability and reliability for this market. Furthermore, Brazil can take advantage of its leadership in biofuel production and become a technology provider for other countries, instead of being only a biofuel exporter.

According to IEA projections (Haug, 2004), consumption of fossil fuels will increase to 5.8 million tonnes by 2030 – 60 per cent more than consumption in 2000. The transport sector will represent more than two-thirds of this increase, and developing countries will be responsible for 71 per cent of the growth. The development of biofuel initiatives in developing countries will thus be important to reduce the “petrodependence” of most of these countries.

The world economic, political and environmental situation appears very promising for biofuel producers. In the case of Brazil, the ethanol industry is booming and there seems to be no doubt about its bright future. However, the same cannot yet be said about the biodiesel industry. A national strategic energy programme, like the biodiesel programme, can only be structured and developed with a long-term perspective. It should not be dependent on short-term fluctuations in the market. Beyond basic supply-and-demand issues, destabilizing fluctuations can also arise from short-term capital movements. Therefore a socially based energy programme regulated and financed by the state should be implemented and carried out until it can survive without government intervention. This was the basis for the long-term success of Proálcool, leading to the current situation where government subsidies and intervention are no longer necessary. Unfortunately, the Brazilian government appears reluctant to regulate biodiesel adequately and seems to be subscribing to the neo-liberal faith in markets.

Still, in the authors' opinion the promises outweigh the threats. The enormous potential of the Brazilian agro-industry, the creativity of Brazilian entrepreneurs, who have survived in a high interest rate environment for many years, and the previous experience with Proálcool lead one to believe that the biodiesel programme will be successful as well.

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## Notes

1. The term Proálcool will be used in this text, although the programme does not exist any more. The production and trade of ethanol are fully liberalized in Brazil.
2. Labour cooperatives of workers, dominated by the truck drivers responsible for workers' transportation between their towns and the cane farms.
3. Hydrated ethanol is used to power ethanol cars. Anhydrous ethanol, or simply ethanol, is used for mixing with gasoline to power gasohol cars, since hydrated ethanol, although cheaper to produce, is not mixable with gasoline.
4. Stillage is a by-product of the sugarcane fermentation process; fertirrigation is fertilization plus irrigation.
5. According to Brazilian legislation (Law 9478 of 6 August 1997), biodiesel is defined as "biofuel derived from renewable biomass, for use in internal combustion motors with ignition by compression or, according to regulation, for the generation of other kinds of energy, that can replace totally or partially the fuels from fossil origin".
6. The use of vegetable oils to replace diesel oil was also considered initially. This option, however, was soon abandoned after some disappointing experimental results.
7. Modified later by Decree 5457, from 6 June 2005.
8. These are acronyms for various Brazilian taxes: PIS = Programa de Integração Social (Social Integration Programme); PASEP = Programa de Formação de Patrimônio do Servidor (Programme for Employee Patrimony Formation); COFINS = Contribuição para o Financiamento da Seguridade Social (Contribution for Social Security Financing).
9. Family agriculture is an internationally recognized expression; but there is no common definition for it. In Brazil, farm size, number of employees and, of course, the fact that overall the main workforce on the farm are family members are taken into account. Again, even within Brazil, the numbers vary from region to region. What is considered family agriculture in the state of Mato Grosso, for example, may not be considered the same in Rio Grande do Sul.
10. The technical specifications of biodiesel in Brazil are defined according to an ANP resolution, "Resolução ANP N° 42, de 24/11/2004".
11. There are limits, however, to the presence of water. Although the process does not require anhydrous alcohol, if the concentration of water is at high levels it will act as a

- competing nucleophile, and the hydrolysis reaction, producing the fatty acids, will compete with the transesterification reaction and thus compromise the yield of biodiesel.
12. Although biodiesel is used here in the singular, it must be remembered that there are many “biodiesels”, depending upon the raw materials and manufacturing processes used.
  13. This chapter was written in October 2005 and revised in September 2006. By the time of the revision, more than 800 million litres of biodiesel had been sold in ANP auctions in the country, demonstrating that there was no reason for the concerns expressed earlier. However, most of this fuel had not yet been delivered, so one cannot be sure about its quality. Most if not all of the biodiesel sold at the moment is made from methanol, showing that the ethanol process is not competitive yet.
  14. According to the Secretary of Industry Commerce and Mining of Mato Grosso state (Alexandre Furlan – oral communication in August 2006), Mato Grosso alone will be able to respond by producing 830 million litres/year of biodiesel from 2007. Two of the plants being installed at the moment deserve comment: one, to be installed in Rondonópolis, will be the world’s biggest biodiesel plant, and the other, which has just been inaugurated in Barra do Bugres, will be the first biodiesel plant coupled to an ethanol distillery.
  15. There were four biodiesel auctions promoted by ANP as of September 2006. The average prices were around US\$0.83/litre. Only biodiesel producers awarded with the social fuel stamp were allowed to participate in the auctions.

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## 7

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## Diversifying the energy portfolio: Competencies and investment opportunities in Nigeria

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*R. S. O. Samuel*

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### Introduction

The steadily increasing price of crude oil and the problems associated with greenhouse gas effects have created an urgent need to develop alternative sources of energy. The possible use of hydrogen as fuel has in recent years been strongly considered as an elixir to cure the world's energy supply problems.

Hydrogen, a non-metallic, monovalent and light element of simple molecular structure, is the most abundant element on earth. Its energy releases do not contribute carbon dioxide (CO<sub>2</sub>) to the atmosphere. It is also known to have about three times the energy content of gasoline on a weight-for-weight basis (Hock, 2006). Unlike fossil fuels, whose combustion produces toxic by-products and greenhouse gases, the by-product of hydrogen combustion is pure and clean water safe for human consumption.<sup>1</sup> Successful development of hydrogen fuel technology will thus greatly revolutionize the world energy sector by cutting both pollution problems and world dependence on oil.

Nigeria is a country with abundant oil and gas reserves. Its large population offers enormous potential for domestic gas usage, though currently much of the natural gas, derived during crude oil production, is simply flared. Recently the country launched a number of domestic and export-driven gas projects with very strong growth prospects. Estimated national gas reserves are currently about 168 trillion cubic feet (TCF), and 10 per cent of this has been committed to the Bonny liquefied natural gas

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*Making choices about hydrogen: Transport issues for developing countries,*  
*Mytelka and Boyle (eds), United Nations University Press, 2008, ISBN 978-92-808-1155-1*

(LNG) project, which is expanding rapidly. With 3 per cent reserved for the upcoming Brass and Olokola LNG projects and 12 per cent earmarked for various new and proposed independent power generation projects, about 127 TCF (76 per cent) of the national reserve remains undeveloped. This offers an enormous investment opportunity.

One possibility is to produce hydrogen through steam reforming of natural gas. Another is to exploit Nigeria's cellulose materials, agricultural products and bio-based wastes to produce biofuels such as ethanol and/or to transform these into hydrogen. This chapter discusses Nigeria's potential for entering the hydrogen economy and the steps that the Nigeria National Petroleum Corporation is taking in this direction.

### Scepticism about the hydrogen economy

Hydrogen does not occur naturally in its pure state, but must be obtained by extraction from its compounds. It is, however, a choice fuel in fuel cells (US Department of Energy, 2006a). Fuel cells are electrochemical devices used to convert the chemical energy of fuel oxidation directly into electricity without having to apply combustion technology (Fuel Cell Works, 2006).

The development and application of hydrogen fuel have, however, encountered a number of challenges with respect to safety, storage, time and cost that have led to scepticism about the feasibility and viability of the technology as an alternative energy carrier (Harvey, 2005). Although hydrogen is available in almost all organic and inorganic substances, it bonds strongly to other elements in the compounds in which it occurs. To produce pure hydrogen requires considerable energy to free it from its bonds and purify it. Storing and transporting hydrogen in the quantities needed to guarantee a sustainable energy supply have thus far required that it be liquefied at temperatures below its boiling point of  $-253^{\circ}\text{C}$  ( $-423^{\circ}\text{F}$ ). This involves putting hydrogen gas under very high pressure, in the region of 10,000 psi. Handling liquid hydrogen under these conditions could pose severe safety problems, apart from the increase in cost. The safety challenges result from the fact that hydrogen is odourless and burns with a colourless flame that is intensely hot locally. It ignites easily, and any leak may not be readily detectable. With its low density at atmospheric conditions it can diffuse rapidly – a property that could make it attractive to terrorists.

In spite of the scepticism surrounding the use of hydrogen, there is considerable enthusiasm and optimism within the industry (Hock, 2005; Broehl, 2006). This can be seen in the amount of resources committed to the development of hydrogen technology. Of great importance is the

extensive collaboration of the US Department of Energy with various organizations in research efforts designed to develop cost-effective production, storage and transportation methods for hydrogen fuel (US Department of Energy, 2005a).

The issue of safety has also been raised (Fuel Cell Store, 2006b: 1015). Hydrogen is believed to be safer than hydrocarbon fuels if properly used (Vincent, 2004). Although its use requires lots of safety precautions, its inherent characteristics<sup>2</sup> means it produces no pollution and thus has little impact on the environment. Because it is currently being produced and/or used in refineries and petrochemical and food-processing plants all over the world, safety issues surrounding its storage and transportation have been well resolved. For the emerging hydrogen economy, the US Department of Energy (2005a) has articulated safety guidelines for proposed projects.

With the amount being spent on research and the investment efforts in the industry, there is no doubt that hydrogen will be the future energy carrier for both commercial and domestic applications. Some fully developed areas of the technology are already being commercialized (Fuel Cell Store, 2006a).

## Generation of hydrogen

The most common ways of producing pure hydrogen gas can be broadly classified into fossil-fuel and water-based methods (Fuel Cell Store, 2006b: 1013; US Department of Energy, 2006b). However, other methods, such as biomass gasification and pyrolysis, are fast developing.

### *Natural gas reforming*

Hydrogen can be produced from coal, gasoline, methanol, natural gas and other fossil fuels. The amount of hydrogen obtained by this method will largely depend on the hydrogen-to-carbon ratio of the hydrocarbon used. Natural gas and methane are known to have the best hydrogen-to-carbon ratio. Production of hydrogen from natural gas is generally achieved by steam reforming. The process, which occurs in two steps, yields mainly hydrogen and carbon dioxide. A relatively efficient (70–90 per cent) method is the source of most hydrogen used in the chemical and petroleum industries. The carbon dioxide produced is generally sequestered and stored in tanks, and can be useful in the manufacture of fire extinguishers. The cost of hydrogen produced by steam reforming is greatly affected by fluctuations in the price of natural gas.

### *Electrolysis and photolysis*

Water-based methods of hydrogen generation are centred on electrolysis and photolysis. While electrolysis uses electricity to split water into its constituent elements, hydrogen and oxygen, photolysis uses sunlight in the presence of photovoltaic semiconductors and electrolyzers or algae and bacteria to produce hydrogen.

The water electrolysis process requires electricity to implement. Thus, relative to steam reforming of natural gas, electrolysis is very expensive: the electrical inputs in the process account for about 80 per cent of the total cost. This cost is reduced when the process is coupled to renewable energy sources like solar, wind or hydroelectric. Photolytic processes, although promising, are still in the research and development stages.

### *Biomass gasification*

Hydrogen can also be produced from the hydrogen-rich biomass of cellulose materials and agricultural or biological wastes. The process involves converting the biomass into hydrogen-rich vapour which is condensed into pyrolysis oil and then steam reformed to generate pure hydrogen. This process could yield 12–17 per cent of hydrogen by weight. With the increasing price of crude oil and natural gas, and the high electricity demand for water electrolysis, biomass gasification will probably be the most economically viable method for future hydrogen generation.

## The Nigeria National Petroleum Corporation

The main platform for Nigeria's participation in the global oil industry is vested in the Nigeria National Petroleum Corporation (NNPC). The mandate of the corporation includes:

- by 2010 build up the national crude oil reserves to 40 billion barrels from the present 33 billion, and increase production levels to 4.5 million barrels per stream day (mbpd) from 2.7 mbpd
- commercialize the vast natural gas resources
- facilitate local participation in the industry by fast-tracking technology transfers and harnessing collaborations within the economy
- maintain domestic self-sufficient supply and distribution of petroleum products and derivatives via a market-oriented downstream sector
- transform the national economy from oil-dependent monoculture to an industrial polyculture using the petroleum sector as a springboard.

The NNPC is actively involved in exploration, refining, petrochemicals and transportation, as well as marketing activities. These operations are

driven by the group managing director's office via four directorates: exploration and production, refining and petrochemicals, finance and accounts, and corporate services. These activities are implemented through a number of strategic business units, two of which are partly owned and several others are associated companies.

Exploration and production activities are implemented by several wholly owned companies.

- Integrated Data Service – involved in seismic data acquisitions, interpretations and oil-block mappings.
- Nigerian Petroleum Development Company – oil-block acquisition, development and management of production facilities to achieve production quota.
- Nigerian Gas Company (NGC) – natural gas gathering, processing and distribution; management of national fuel gas supply network.
- National Petroleum Investment and Management Services – supervises Nigerian government investments in production-sharing and service contract agreements with joint-venture partners like Shell, Chevron, Mobil, Agip and others.
- National Engineering and Technical Company – provides engineering services within the oil and gas industry; involved in feasibility studies, conceptual design, basic and detailed engineering design, procurement, construction supervision and project management.
- Duke Oil – a partly owned company involved in drilling and production activities.

The NNPC refining and petrochemicals activities are implemented via the Port Harcourt Refining Company (PHRC), Warri Refining and Petrochemicals Company, Kaduna Refining and Petrochemicals Company (KRPC) and Eleme Petrochemicals Company (EPCL). The Nigerian government is currently involved in a process of disinvesting 51 per cent of its holdings in both the PHRC and KRPC. Seventy-five per cent of the shares in EPCL have already been sold to the Indorama Group of Indonesia.

The marketing activity of the NNPC is implemented through the Pipelines and Product Marketing Company (PPMC), Hydrocarbon Services of Nigeria (HYSON) and the partly owned Calson. The PPMC is responsible for domestic distribution of all petroleum products; it also manages the vast product depots and associated pipeline networks. HYSON is responsible for offshore bulk procurement of petroleum products to offset any shortfall in domestic supplies, and also exports any excess capacity if necessary. Calson, partly owned by the NNPC, is an offshore company that oversees NNPC interests in oil and gas businesses outside Nigeria.

Hydrogen is produced at EPCL. Conceived as a complex and designed for development in three stages, it is presently in its first stage:

Table 7.1 Hydrogen generating capacity available within the NNPC operation

NNPC company	Hydrogen generating unit	Capacity (MT/Y)
PHRC	Catalytic reformer	6.84
KRPC	"	11,600/9,700*
WRPC	"	17,784
EPCL	Olefins cracker	1,800

\* Actual utilized capacity

this consists of a 997 KT/Y Kellogg Brown & Root licensed Olefins cracker designed to produce 300 KT/Y polymer-grade ethylene for use by 270 KT/Y Nova Chemicals of Canada licensed solution-phase polyethylene and 22 KT/Y IFP of France Alphabutol Butene-1 manufacturing processes. The Olefins cracker is also designed to produce 126 KT/Y polymer-grade propylene used by an 80 KT/Y Basell of US licensed polypropylene manufacturing process. Also generated in the cracker operation is about 1,800 MT/Y of pure hydrogen gas, some of which is used for hydrogenation processes within the cracker operation and the balance delivered to the polymer plants for use as a chain terminator in the polymerization processes for polyethylene and polypropylene.

For the cracker to produce more hydrogen, expansion of the plant capacity far beyond its present size will be needed. However, the cracker also produces 33.1 KT/Y of methane-rich steam (98.36 per cent methane and 1.64 per cent hydrogen by weight), which is directed to the complex fuel-gas system. This stream can be developed into a feedstock for a steam-reforming process for generating hydrogen. The available hydrogen generation capacity within the NNPC is indicated in table 7.1.

## The NNPC's move into natural gas and biofuels

The current democratic government in Nigeria has initiated a far-reaching reform agenda in all sectors of the national economy. Its purpose is to install the catalysts needed to build a robust economy that will attract a continuous flow of investment and thus increase income-generating capacity while diversifying the economy itself. The government plans to support its reform agenda with generous investor incentives.

As part of the government's reform agenda, the NNPC, a major element in the Nigerian economy, is undergoing a transformation process aimed at repositioning the corporation to realize fully its vision of becoming a world-class oil and gas company. This transformation programme is

implemented via a project labelled PACE, aimed at positioning (P) and aligning (A) the corporation for higher performance by creating (C) appropriate processes and systems for global competitiveness and enabling (E) and empowering the human capital that drives the processes to achieve organizational goals. A deliberate policy is to open NNPC operations to private sector participation, in line with global trends in modern business practice and government deregulation, liberalization and privatization policies.

With its large oil reserves (30–40 billion barrels), vast gas reserves (168 TCF) and massive amounts of fertile land with coal and other solid minerals like bitumen, Nigeria offers abundant investment opportunities. In order to boost investment in the economy, the Nigerian government planned to spend US\$30 billion in the petroleum sector by 2008: this governmental effort is aimed at creating about 10,000 new jobs in this sector alone.

### *Natural gas*

One of the main objectives of the investment in gas development will be the commercialization of compressed natural gas (CNG) for automotive applications. This technology is presently being harnessed by the Nigerian Gas Company, a subsidiary of the NNPC. The project, which is progressing rapidly, has pilot plants for automotive CNG refilling in the NGC's Warri and Egbin stations. Presently the NGC is shopping for technology to adapt fuel-injection vehicles for CNG use. To accomplish this goal, a team of NGC engineers have been sent to Argentina to understudy and adapt its technology for application in Nigeria, starting with the NNPC mega-stations. For this purpose, the company spent about \$500,000 in 2006. The CNG automotive application project offers investment opportunities in CNG filling stations, conversion or adaptation workshops and conversion kits in the country.

Apart from the CNG automotive application project, the NGC is involved in distribution of CNG for both domestic and industrial uses and is also engaged in the West African Gas Pipeline project. However, Nigeria is already an exporter of LNG: the first cargo was shipped from the Nigerian Liquefied Natural Gas Company in Bonny in November 1999; as a result of this, further investment in CNG export terminals is very unlikely.

### *Biomass*

The Nigerian energy sector is regulated by the Nigerian Energy Commission. The commission has developed a comprehensive energy policy for

the country, which was approved in April 2003 (Government of Nigeria, 2003). The policy acknowledges the significant biomass energy resources in Nigeria which can be harnessed for power generation. The by-products can be used as fertilizers, thus reducing dependence on chemical fertilizers.

The policy seeks to integrate biomass energy resources with other energy resources through the adoption of an efficient conversion technology, and thus develop a biomass technology for the country and maximize the use of agricultural residues, animal and human wastes for energy generation. It is envisaged that this will help reduce health problems associated with biomass incineration at open waste-dumping sites scattered across the country. The strategies to be adopted to accomplish this, as spelt out in the policy, include development of extension programmes, promotion of R&D efforts, establishment of pilot plants, creation of an enabling environment for local and foreign investors and development of the requisite manpower requirements.

The recent policy decisions and government investment efforts have generated NNPC interest in alternative energy technologies. This resulted in the creation of the Renewable Energy Division (RED) within the corporation in July 2005. The division's activities have commenced with an automotive biomass ethanol programme which involves securing alternative fuel through the use of biomass technology to produce ethanol from sugarcane and fresh cassava. RED, an NNPC greenfield business initiative, will be responsible for the development of the biofuels industry in Nigeria as a means to reduce carbon dioxide releases, improve air quality and thus contribute to a reduction in global warming as required by the Kyoto Protocol, to which Nigeria is a signatory. The programme will help to integrate the agricultural sector with the petroleum industry, thus creating jobs, boosting research activities and opening new investment opportunities.

As part of the Nigerian government's programme aimed at stimulating the transition to sustainable energy by developing an indigenous biomass technology using cassava and sugarcane, the NNPC's RED is collaborating with several universities and research institutes in Nigeria. Those involved in cassava research include the University of Agriculture in Abeokuta, the University of Markurdi, the International Institute for Tropical Agriculture in Ibadan and the National Root Crop Research Institute in Umudike. For now, the only collaborator involved in sugarcane research is the National Cereal Research Institute in Pategi.

Collaborative research efforts are presently aimed at realizing the government's automotive biomass ethanol programme. When the biogas technology is fully developed and deployed, it is envisaged that another

unit will be needed within the NNPC RED for the production and distribution of hydrogen. This initiative, when adopted, will create further extensive investment opportunities, as partners will be required in the areas of production, storage and distribution infrastructures for hydrogen fuel.

## Conclusion

Nigeria is a country with abundant hydrocarbon resources. Until recently this has been a major impediment to thinking about the development of alternative, non-polluting energy resources. However, under the present democratic government a far-reaching reform agenda has been launched. It includes a major effort at developing local research into energy-related technologies and a considerable increase in investment in this sector.

As part of this process, in April 2003 the Nigerian Energy Commission approved a comprehensive energy policy for the country. The policy takes account of the country's huge landmass coupled with its favourable climatic conditions for agriculture, both of which enhance its potential for biomass technology. This potential is presently being tapped in the new government alternative energy initiative to produce ethanol fuel for the automotive sector. The NNPC's RED is part of the Nigerian government's programme to stimulate a transition to sustainable energy by collaborating with universities and research institutes in the development of an indigenous biomass technology using cassava and sugarcane.

The national policy also recognizes hydrogen as an environmentally friendly combustible fuel that generates energy with an excellent safety record, and it acknowledges the potential for hydrogen to replace fossil fuels in energy generation in the transport sector and for hydrogen fuel cells to play a role in electricity generation. The policy seeks to integrate hydrogen as an energy source into the country's energy mix, so as to develop local production capacity and eventually ensure the use of hydrogen as a preferred energy source.

Despite its considerable activities in crude oil drilling and production in the Niger delta region, most of the natural gas derived during crude oil production has been flared. Since 1999 a small percentage of Nigeria's natural gas resources has been exported as LNG; more recently, a project to develop CNG for commercialization in the domestic market has been initiated. However, the country also offers potential for investment in steam reformation projects for hydrogen production. Currently there is no research effort in steam reforming of either biogas or natural gas to produce hydrogen for the automobile sector to match the biogas initiative already under way.

## Notes

1. This process has already been adopted in the space-shuttle operations.
2. When ignited, hydrogen produces no residual soot and very little radiant energy.

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## 8

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## Egypt's policies and measures for sustainable transport

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*Ibrahim Abdel Gelil*

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### Introduction

Egypt is the largest Arab country, with more than 75 million inhabitants, and is the second most populous country in Africa. The population is growing by some 1–1.5 million per year, and is expected to reach 80 million by 2015. Almost 50 per cent of the population live in urban areas, and the rest in compact rural settlements surrounded by intensively cultivated irrigated land along the River Nile. Together with the growing economy, this is inevitably putting more pressure on the country's natural resources, environmental quality and infrastructure, including the transport system.

The transport sector is a major consumer of fossil fuels and therefore contributes a significant share of the country's emissions of greenhouse gases (GHGs). In 2003–2004 the transport sector was responsible for 29.16 per cent of overall energy consumption and about 31.6 million tonnes of CO<sub>2</sub>, representing nearly 26 per cent of the energy-related CO<sub>2</sub> emissions (OEP, 2004).

To mitigate the environmental and health impacts of the transport sector, the government has implemented a number of policies and measures, including the commercialization of alternative fuels such as compressed natural gas (CNG), and the demonstration of other technologies such as electric vehicles and fuel-cell buses (FCBs).

This chapter outlines the interlinkages between transport, energy and environmental quality in Egypt, and reviews the air quality management

programmes that are being implemented or planned. Further, it discusses different policy options available to Egypt in the long term to foster a sustainable transport system. These include the electrification of the rail-road system, building an underground metro for the Greater Cairo area, phasing out leaded gasoline and demonstration projects for electric and hybrid buses. Initially the option to create a fuel-cell bus demonstration project was also considered. The reasons for its postponement in the first few years of Egypt's planned sustainable transport programme are discussed in the concluding section.

## Energy situation in Egypt

The energy sector plays a substantial role in the economic development of Egypt and fulfils domestic energy demands for petroleum products, natural gas, and electricity. It contributes to macroeconomic variables such as gross domestic product (GDP) (9.9 per cent in 2003–2004) and investments (20.6 per cent of total investments in 2003–2004) (OEP, 2004).

Egypt is an oil producer and an emerging natural gas exporter. Though net exports of crude oil and petroleum products have declined in recent years, higher prices on world markets and new gas discoveries have pushed Egypt's oil revenues upward. Oil exports were equivalent to 37.6 per cent of total commodity exports in 2003–2004. The country also began exports of liquefied natural gas (LNG) from its first terminal in January 2005, adding another hard-currency revenue stream; this was expanded in late 2005 with the completion of the second LNG export terminal (Energy Information Administration, 2005).

Egypt's main energy resources are oil, natural gas, coal and hydropower, in addition to good potential in renewable energy resources. Oil reserves are estimated at approximately 3.6 billion barrels, most of which are located in the Gulf of Suez. Oil production accounted for about 34 million tonnes (Mt) at the end of 2004, of which nearly 95 per cent was consumed domestically. Natural gas reserves equal nearly 67 trillion cubic feet (TCF). Natural gas is mainly used as feedstock into the Egyptian petrochemical industry. At the current annual production level of about 941 billion cubic feet (BCF), however, it is expected that natural gas will play a crucial role in the country's future fuel mix and commodity exports.

Hydropower is the third major energy resource in Egypt. Most of the Nile's hydropower potential has already been exploited to generate about 13 TWh of electricity per annum. As shown in figure 8.1, oil and gas accounts for about 95 per cent of total commercial energy produc-

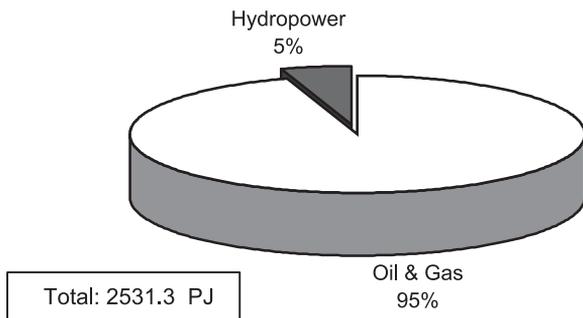


Figure 8.1 Commercial energy production in Egypt (2001–2002)

tion, while hydropower represents the remaining 5 per cent (Abdel Gelil, 2005). Egypt also has limited coal reserves estimated at about 27 Mt.

In addition to its commercial energy resources, Egypt has good potential in renewable energy resources. These include solar, wind and biomass such as fuelwood, agriculture wastes and dried animal dung, which are used in some rural areas to meet part of the energy demand. It is estimated that about 3.6 Mt of oil equivalent of biomass energy is consumed annually. Due to its geographic location, Egypt enjoys sunshine all year round with a direct daily solar intensity range of 1,970–3,200 kWh/m<sup>2</sup>. Wind-speed assessments have shown that there are locations in Egypt where average annual wind speed is about 30 km/hr, making these suitable for producing power from commercial wind turbines (Abdel Gelil, 2005). Thus far, the contribution of solar and wind in the country's energy production is underexploited. The Egyptian renewable energy strategy sets a target to provide 20 per cent of Egypt's electricity demand by renewable energy resources, mainly solar, wind and biomass applications, by the year 2020. Currently there is 140 MW of grid-connected wind capacity located by the Red Sea coast. The target is to increase that capacity to reach 850 MW by the year 2010 (New and Renewable Energy Authority, 2006).

## The Egyptian transport sector

The demand for energy in the transport sector has been growing in tandem with the population, economic growth and the increasing pace of urbanization. The Transport Sector Development Plan, which covers the years to 2017, includes measures to promote public passenger transport and encourage a modal shift of cargo transport from road to railways

and inland waterways; it envisages government investments of hundreds of millions of dollars. In addition, the government has for many years pursued a policy of gradual liberalization and privatization of the transport sector (EEC, 2005).

Road is the dominant mode of internal transport in both passenger and freight operations. In 2003–2004 the volume of people transported by road had reached nearly 115.6 billion passenger/km, while freight transport amounted to nearly 43.1 billion tonnes/km (State Information Service, 2006).

For railways, the policy goal is a revitalization of the sector and the development of better service quality by Egyptian National Railways (ENR), which is state-owned and highly subsidized. While rail has a relatively high share of the domestic passenger market, its share of the freight market is very low (only 8 per cent of the total tonnes/km capacity). The rail system delivered 76.1 billion passenger/km in 2003–2004; while freight was only 4.7 billion tonnes/km. ENR is presently undertaking significant investment in order to modernize and upgrade the railways and extend its network (table 8.1).

Egypt's inland waterways, the River Nile and canals, are severely underutilized for transport. Primarily designed as an irrigation system, in 1995 the inland waterways carried approximately 3.6 million tonnes of freight, which represented only 3.3 per cent of the total tonnes/km transported (EEC, 2005).

The energy consumption of freight transportation is another area with rapid growth. What characterizes Egypt's freight system is that it is domi-

Table 8.1 Egypt's main transport indicators

Indicator	2002–2003	2003–2004
<i>Railways</i>		
Passenger/km (million)	46,185	76,090
Ton/km (million)	38,444*	4,758
Railway length (km)	9,432	9,467
<i>Roads</i>		
Passenger/km (million)	113,570	115,845
Ton/km (million)	41,450	43,110
<i>River transport</i>		
Ton/km (million)	309	2,375
<i>Pipeline transport</i>		
Million tons	6,489	6,680

Source: State Information Service (2006).

\*This figure, although given in the SIS document, appears far too high and is most likely an error.

nated by road transport, with a 90 per cent share of all freight, while the opportunities for more energy-efficient rail and inland waterway transport are clearly underutilized; the transport demand is concentrated on a few transport corridors starting from or ending in Cairo; and the transport patterns are influenced by the imbalance between exports and imports (the value of imports being about twice the value of exports in 2002).<sup>1</sup>

### *Urban transport*

Currently mobile emissions are one of the major sources of air pollution in the country, producing about 25 per cent of Egypt's energy-related CO<sub>2</sub> emissions. This is particularly acute in Cairo, a megacity of 17 million people and the country's major urban, industrial and financial agglomeration. Demand for mobility in Cairo has greatly outpaced the capacity of the public transportation system. The gap has been primarily filled with privately owned and operated shared taxis (so-called informal transport) and the use of private cars. As the Cairo Regional Area Transportation Study (UNDP, 2005) pointed out, congestion has become a major problem and the air quality has deteriorated to an alarming level.

The number of vehicles registered in Egypt increased from nearly 3.6 million in 1992 to almost 6.6 million in 2005 (Egypt Information Portal, 2007). About 50 per cent of the total vehicles were registered in the Cairo metropolitan area. Significant features of the Cairo vehicle fleet include:

- the average vehicle age is relatively old
- passenger cars are expected to constitute the fastest-growing category over the next few years due to economic growth, gradual decreases of tariff duties on imported cars and increased numbers of locally assembled ones
- almost all trucks and buses use diesel fuel and have old-generation diesel engines
- there are essentially no diesel-powered passenger cars because these have been prohibited by law.

The number of public buses has not been expanding at a significant rate due to capital constraints and the growth of the underground metro system. Public transport in Cairo consists of two generic groupings: formal and informal services. Formal urban public transport services are provided by the state-owned Cairo Transient Authority (CTA), the Greater Cairo Bus Company (GCBC) and the Cairo Metro Organization, which runs the urban heavy-rail service. The informal sector consists predominately of route-specific shared taxis, operated by the private sector using minibuses with typical capacities of 11–14 seats.

In 2001 public transport services carried a total of 12.44 million trips every weekday, or 68 per cent of the total (public and private) motorized trips generated within the metropolitan region. Shared taxis (microbuses) carried some 6.5 million daily passengers, or roughly half of daily motorized public transport trips. CTA buses accounted for a further 3.5 million daily trips, and the metro for slightly more than 2 million trips per day – most of these riders had previously travelled by bus, microbus and taxi. Other modes of transport contribute about 0.4 million trips per day. Formal bus services are constrained by government control on the route structures they offer and the fares they may charge. Concurrently, the ageing fleet (the average bus age is now in excess of 12 years) must serve ever-expanding urban centres. As a result, service frequencies are declining throughout the system. Although the network has increased from 6,100 to 10,100 kilometres over the past decade, fleet size has only increased from 3,700 to 4,400 buses (some three-quarters of which are considered operational). Thus, crowding on buses sometimes reaches intolerable levels (Thompson and Nagayama, 2005).

Air quality in Cairo has been partially monitored since the early 1970s. In 2004 the measurements revealed that the average annual concentration of SO<sub>2</sub> exceeded the limits set by Egyptian air quality standards and the average annual concentration of NO<sub>2</sub> exceeded the WHO limits in the most congested areas of the city. Due to traffic congestion, Cairo city centre had the nation's highest concentrations of CO<sub>2</sub> (6.8 mg/m<sup>3</sup>) (Egyptian Environmental Affairs Agency, 2004).

## Policies to improve air quality

Egypt's contribution to the global emission of greenhouse gases is relatively minimal, yet given its growing population, its limited fertile land and the concentration of major economic activities in the coastal zones, the potential social and economic impacts of climate change could be devastating for the country's future development.

The first national communication to the UN Framework Convention on Climate Change (UNFCCC) outlined the overall national policy to address the challenge of climate change. The climate change action plan not only considers adaptation measures but also mitigation actions aimed at the reduction of carbon dioxide and methane. Supported by bilateral and multilateral development agencies, a number of mitigation options were assessed, of which some are being implemented. Mitigation actions to reduce CO<sub>2</sub> deal with energy, industrial processing and transport sectors, while those for CH<sub>4</sub> mainly cover the agriculture/livestock and waste sectors (Egyptian Environmental Affairs Agency, 1997).

Mitigation options for the transport sector outlined in the first national communication included the following.

- Energy efficiency through improvement of vehicle maintenance and tuning-up of vehicle engines.
- A programme to use compressed natural gas as a vehicle fuel.
- Reintroduction of electrified railways in intercity and intra-city transport.
- Intensifying the use of environmentally sound river transport systems.
- Extending metro lines to newly developed cities.
- Encouraging private sector participation in financing and managing the new metro lines.

Thus addressing the problem of air quality has been the focus of environmental policy in Egypt for many years. The national air quality management programme includes a broad array of policies and measures to curb emissions of pollutants from both stationary and mobile sources. A brief outline of those policies and measures relevant to the transport sector follows.

#### *Vehicle emissions testing and tuning programme*

Inspections of 13,000 vehicles operating in Cairo in 1999 showed that hydrocarbon and CO emissions generally exceeded the Egyptian vehicle emission standards by 12 per cent and 17 per cent, respectively. A total of 66 per cent of the vehicles inspected were found to comply with national standards, while 34 per cent failed to pass. Based on this pilot experiment, a vehicle emissions testing, engine-tuning and certification programme was established in Cairo in order to improve fuel efficiency and air quality. The programme has subsequently been progressively introduced to other cities in Egypt, and vehicle emission testing and certification have become mandatory for vehicle licensing.

#### *CNG as a transport fuel*

As part of the national policy to switch from oil to natural gas in all consuming sectors, the use of natural gas as a transportation fuel was endorsed as a means to improve air quality and public health. In the early 1990s the government recognized that utilizing Egypt's abundant natural gas as a transportation fuel could, in addition to developing a new market for natural gas, make a significant contribution towards improving air quality and protecting public health.

As Egypt has enjoyed remarkable success in the exploration and production of natural gas, supported by the success of pilot projects, the Egyptian government encouraged the private sector to begin commercializing

natural gas vehicles (NGVs). In December 1994 the first company to convert gasoline vehicles to natural gas was formed.<sup>2</sup> This programme proved to be successful. By the end of 2005 there were six operating CNG companies,<sup>3</sup> 93 CNG fuelling stations and about 63,000 CNG vehicles in use, 75 per cent of which were taxis, mainly in Cairo. This represents about 3 per cent of the world's CNG vehicles. A primary key to the NGV industry's success in Egypt is a package of incentives offered by the government, including five-year tax holidays for CNG companies, low-cost conversion charges for car owners and the attractive price differential between CNG and gasoline. At 45 piastres per cubic metre (equivalent in energy content to a litre of gasoline), CNG is less than half the gasoline price of 1.00 LE (Egyptian pound) per litre. In addition, a typical vehicle conversion kit, which is currently imported, costs the customer 5,000 LE (about US\$870). Owners of high-fuel-use vehicles, such as taxis, can recover the cost of conversion in as little as six months from fuel savings alone. This clearly explains why taxis have been the most converted fleet.

Another exciting development for Egypt's CNG growth was the EEAA/USAID-sponsored \$63 million Cairo Air Improvement Program (CAIP). This initiative focused on improving Cairo's air quality through reducing harmful emissions from lead smelters and vehicle exhausts. Part of the programme included providing 50 dedicated CNG public-transit buses to the CTA and GCBC. The bus bodies are locally manufactured, but the CNG engines are manufactured by Cummins in the United States and the rolling chassis were supplied by a US manufacturer. Key challenges for the government have been to fund the conversion of the some 3,500 public buses operating in Cairo and change the price differential between CNG and diesel, which is heavily subsidized.

With this ongoing encouragement from the Egyptian government and the oil industry, the CNG commercialization initiative in Egypt will continue to provide a successful model for other countries to emulate. In addition, as the natural gas supply network expands into new areas, vehicular natural gas will also become possible for these regions. Egypt is now recognized as having one of the top 10 most successful CNG commercialization programmes worldwide (Chapel, 2002).

### *Electrification of railways*

Historically, Egypt was second to the United Kingdom in introducing railways in the 1880s. Rail plays a vital role in passenger transport in Egypt, with a total share in 2003–2004 of about 39 per cent. Most of the rail system operates on gas oil (diesel). A preliminary study on the feasibility of railway electrification was carried out in 1999, using the Cairo–

Alexandria line as a test case. As Egypt is a net importer of gas oil, which is subsidized by the government for domestic use, and as part of the government's "switching to gas" policy, the anticipated environmental and economic benefits of rail electrification would include fuel savings (nearly 15 per cent of the electricity is produced from hydropower and the remaining 85 per cent from oil and gas), lower operation and maintenance costs and improved economic efficiency.

### *Cairo underground metro*

A major step to upgrade Cairo's transport system has been the construction of an underground metro, the first of its kind in Africa and the Middle East. The 63 km underground network links the three governorates comprising Cairo metropolitan region: Cairo, Giza and Qalyoubia. The network comprises two lines: line 1, Helwan–El-Marg, and line 2, Shubra–El-Kheima–Mouneeb. Line 1, which was completed in 2000, is 44 km long and currently carries 1.5 million passengers per day. Line 2, 19 km long, was completed in 2005 and is now used by 1.2 million passengers per day.

Future plans include building a third line from Cairo International Airport, east of Cairo, to Imbaba in the west. The new line, about 33 km in length, will have a design capacity of 2.1 million passengers per day. It is expected to take 13 years to complete. Three additional lines are also envisioned for the year 2022 (Egyptian Tunneling Society, 2004).

### *Phase-out of leaded gasoline*

A major objective of air quality initiatives in Egypt has been to reduce the ambient lead concentration to below the WHO level of 0.5 mg/m<sup>3</sup>. Lead emission sources are mainly lead smelters and leaded gasoline. The 1999–2000 inventories of stationary lead emission sources in the Cairo metropolitan area clearly showed that secondary lead smelters are the most significant sources of lead emissions in the city (Egyptian Environmental Affairs Agency, 2001). Of the total emissions in 2000, 79 per cent came from lead-smelting activities, compared to 82 per cent in 1999, and 20 per cent resulted from the combustion of heavy fuel oil, compared to 18 per cent in 1999. According to the study, lead emissions decreased about 30 per cent in 2000 compared to 1999. The reduction in the total emissions is primarily due to a production decrease in the lead-smelting industry in Greater Cairo as well as switching to natural gas instead of oil in the industrial and power generation sectors. Lead-free gasoline has been introduced in the Cairo metropolitan area and has been gradually introduced to the rest of the country (ibid.). In Cairo 100 per cent of

gasoline is now lead-free; in rural areas this falls to about 80 per cent. In addition, attempts are being made to relocate lead smelters to more remote areas and, as explained earlier, promote further expansion in use of CNG in transport.

### *Demonstration of electric buses*

The Global Environment Facility (GEF) is sponsoring a project to demonstrate electric and hybrid buses in Egypt. Initially these were intended to be used as shuttles around the historic site of the Pyramids outside Cairo. The buses, procured under a GEF-sponsored project entitled “Introduction of Viable Electric and Hybrid Electric Bus Technology in Egypt”, were expected to begin operation in early 2001. In the proposal this was conceptualized as part of a longer-term transition to clean technologies that included electric and hybrid-electric as well as hydrogen fuel-cell buses, since all three are based on the same propulsion technology – electric motors with power electronics. The difference lies in the energy conversion or storage device. Issues such as drive-train maintenance, operator training and technology training of engineers are common to all three platforms. At present only two electric buses are operating, both at the Temple of Luxor, one of the world’s historic heritage sites, instead of the planned plateau of the Pyramids. Each bus is generating a daily income of around US\$1,200. The demonstration, during which these buses were operating for two years, has now come to an end, and the UNDP is preparing a final project evaluation with the hope that the Egyptian government will replicate the same experience in other similar sites.

### The fuel-cell bus demonstration project

Under Egypt’s climate change action plan, the Egyptian Environmental Affairs Agency submitted a concept paper to the GEF in 1998 requesting support for a fuel-cell bus demonstration project in Cairo. As part of the GEF strategy to develop FCBs for the developing world, and consistent with the objectives of GEF Operational Program OP-11, Sustainable Transport, the GEF council decided at its meeting in November 2000 to develop the five FCB projects then in its pipeline – in Egypt, India, China, Mexico and Brazil. The development objective was to reduce long-term GHG emissions from the transport sector in the GEF programme countries (Global Environment Facility, 2004).

According to Egypt’s GEF project brief, the FCB demonstration project, though it was to be located in Cairo, would deal with the wider Mid-

dle Eastern and African bus market. Further, it was recognized that conditions in Egypt would allow the opportunity for performance testing of fuel cells and thus provide valuable information for similar climatic/geographic regions in the world. The proposed demonstration project had eight specific objectives (Global Environment Facility, 2000).

- Verify the efficiency, operability, reliability and maintenance requirements of FCBs.
- Build up local experience and capability in both personnel and parts' supply for operating and maintaining FCBs and hydrogen facilities.
- Demonstrate to the public, and gain their acceptance of, the operability, safety, high performance and low emissions of FCBs and hydrogen production and fuelling facilities.
- Provide opportunities for local bus manufacturers to integrate and assemble FCBs with imported engines and chassis.
- Induce universities and research institutes in Egypt to get more involved in fuel-cell technology.
- Establish policy changes and codes/standards to promote the use of fuel-cell technology.
- Increase the volume demand for FCBs, jointly with other GEF FCB demonstration projects, to accelerate commercialization.
- Accumulate experience as input to FCB developers to improve their products further and accelerate commercialization.

The learning inherent in these objectives would also enable Egypt to become a regional or worldwide FCB supplier. This would be accomplished by building upon the manufacturing expertise gained during the demonstration project and the low labour cost in Egypt. The new business created might thus have contributed significantly to the nation's economy.

The project was designed to build and operate eight FCBs over a period of five years. These buses would be put into regular revenue service to gain real-time test data and experience. Over the test period this bus fleet was expected to accumulate a total of about 1.6 million km.

### *The systems optimization study*

As part of the proposed project, a systems optimization (feasibility) study was undertaken by Bechtel (2000). The study covered both the production and the distribution of hydrogen. It showed that the best system to supply hydrogen for full-scale commercial deployment of FCBs in Cairo was a centralized natural gas reforming plant with the hydrogen delivered to the bus garages by a gas pipeline and the CO<sub>2</sub> recovered and sequestered in a spent gas well. This system was selected from among eight alternatives based on the supply of energy and other local conditions in

Egypt, as well as selection criteria such as the cost of CO<sub>2</sub> reduction, amount of CO<sub>2</sub> reduced, cost of bus driving, capital required and ability to undertake investment.

For the demonstration project, the study noted that a packaged electrolyser unit, including high-pressure hydrogen gas storage cylinders, hydrogen compressors and dispensers, would have to be purchased and installed at the host garage to meet the hydrogen requirement. The centralized reforming plant, hydrogen pipeline and CO<sub>2</sub> sequestration facility (pipeline and injection pumps) are all proven technologies and thus it was not regarded as essential to demonstrate them in this project.

In its economic analysis the study found that FCBs could be more economical than diesel buses even with the additional costs of hydrogen production, transport, storage, compression and dispensing. One of the main reasons is that public buses in Cairo run very long hours every day, and maintenance is the single largest cost item of bus operation. Bechtel (*ibid.*) argued that the savings on maintenance costs that would result from the purchase of new buses and the higher reliability of FCBs because of fewer moving parts when compared to a conventional internal-combustion engine would be more than enough to compensate for the hydrogen cost.

A baseline study drawing upon data for eight diesel buses operating for 1.59 million km showed that these vehicles could be expected to emit approximately 3,312 tonnes of CO<sub>2</sub>. The FCBs would emit only water vapour, but the production of the electricity needed to produce hydrogen via electrolysis would result in the emission of 3,127 tonnes of CO<sub>2</sub>. The net CO<sub>2</sub> benefit from this project would therefore be 185 tonnes. Additional expected emission reductions resulting from the implementation of the demonstration project are illustrated in table 8.2.

### *Local capabilities to support fuel-cell technologies*

As part of the GEF project cycle, a “project development facility” was undertaken to justify the GEF funding. This involved an assessment of Egypt’s capabilities to support the fuel-cell technology. As mentioned earlier, Egypt has a large potential for wind power, huge solar resources and an abundance of natural gas that could easily be used to produce hydrogen. In addition, Egypt has extensive experience in operating refineries, petrochemical complexes and fertilizer and chemical plants that currently produce large quantities of hydrogen for their own consumption. The KIMA plant in Aswan, for example, uses hydropower to produce H<sub>2</sub> by electrolysis. Three fertilizer plants and eight major oil refineries in Alexandria, Talkha and Suez are producing H<sub>2</sub> by natural gas reforming. Thus producing hydrogen on a large scale is not new to

Table 8.2 Emission reductions and incremental costs due to FCB demonstration in Cairo

	Baseline	Alternative	Increment
<b>Global Environmental Benefits</b>			
CO <sub>2</sub> emissions from buses, tonnes	3,312		(3,312)
CO <sub>2</sub> emissions from H <sub>2</sub> production, tonnes		3,127	3,127
Total	3,312	3,127	(185)
<b>National benefits</b>			
SO <sub>2</sub> emissions, tonnes	3		(3)
NO <sub>x</sub> emissions, tonnes	32		(32)
CO emissions, tonnes	44		(44)
HC emissions, tonnes	7		(7)
Particulates emissions, tonnes	2		(2)
Million passenger km	104	104	-
Part I cost, US\$ million	0.47	9.99	9.52
Part II cost, US\$ million	1.06	12.71	11.65
Total cost, US\$ million	1.53	22.70	21.17

( ) denotes reduction

Source: Bechtel (2000).

Egypt, which already has skilled local operating and maintenance capabilities for its existing hydrogen production facilities.

The bus manufacturing/assembly industry was established more than 40 years ago. There are four major bus manufacturers producing more than 4,000 buses annually. With the exception of NASCO, which is state-owned, the other three are privately owned either through joint ventures with local firms or under direct licence from three global truck and bus manufacturers, Mercedes-Benz, MAN and Scania. These privately owned companies are all equipped with state-of-the-art bus manufacturing and assembly facilities. Thus the build-up of local capability to manufacture and supply FCBs in Egypt is expected to have a high probability of success. The current price of a full-size diesel bus manufactured in Egypt is about US\$120,000, while it is US\$235,000 in the United States and Canada. This large price differential is due to the low labour cost in Egypt and the higher US/Canadian bus standards. Not all the bus manufacturers in Egypt are simply assemblers. Some have their own bus body designs built on imported chassis. So Egypt's local bus manufacturing capacity can contribute to a long-term strategy of producing FCBs.

Another supporting capacity for developing FCB technology is the fact that Egypt has a well-developed CNG industry. The Cairo Transient Authority (CTA) is currently introducing CNG buses through a demonstration project under the EEAA/USAID-funded Cairo Air Improvement Program (CAIP). CNG engines are commercial technology and are an

immediate solution to the pollution problem in Cairo. As the hydrogen refuelling of FCBs uses essentially the same technology as CNG refuelling and the hydrogen production in Egypt will be most likely based on natural gas, the build-up of infrastructure for natural gas distribution and CNG fuelling in the current pursuit of CNG buses will provide a good base for future switching to FCBs.

### *Barriers to the commercialization of fuel-cell buses*

Although the feasibility study showed that Egypt has the potential to develop FCBs, it also identified a number of barriers to the commercialization of FCBs in Egypt at that time (Bechtel, 2000).

- *Costs.* The initial cost of the GEF demonstration project, estimated at around US\$23.5 million, was extremely high. Given that only eight buses were planned, the average cost per FCB would be very high compared to the baseline diesel buses option.
- *Technology uncertainties.* A key issue in the GEF project brief was that this is a new technology. The FCB thus had to compete in terms of efficiency, reliability and cost with the newly introduced CNG buses in Egypt. Reducing the cost of the fuel-cell technology has been always a key concern. However, recent developments have signalled the potential in the long term to overcome these barriers.
- *Safety issues and public acceptance.* Safety concerns would be an issue due to the introduction of FCBs into the public transport system and the exposure of hydrogen use to the general public. In the absence of safety codes and standards, commercialization of this technology would be associated with health and environmental risks. In addition, lack of information and low levels of awareness about hydrogen as a fuel would decelerate commercialization of such technology.
- *Shortage of qualified human resources.* Even though Egypt has an extensive education and research system to produce professionals and skilled labour to serve the FCB industry, there are currently no sufficient knowledge base, research and/or education programmes for hydrogen technologies.
- *Lack of proper regulatory framework.* As the FCB is a new technology, the proper regulatory framework is not yet in place worldwide. International and industry experiences in the short to longer terms would facilitate the development of those regulations, especially in developing countries.
- *Lack of proper infrastructure.* Building hydrogen infrastructure has been one of the major barriers to commercialization of fuel-cell technology worldwide. For nearly two decades Egypt has been building its

natural gas infrastructure, including a national gas grid which recently reached a capacity of 130 million m<sup>3</sup>/day (Soliman, 2005). Given the expected relatively low demand for hydrogen in the transport sector, it would be hard to justify, even in the long term, building a new hydrogen infrastructure in the current Egyptian context.

To overcome these barriers, a package of policy interventions was recommended in the feasibility study (Bechtel, 2000). These included direct financial subsidies, soft loans or tax credits for the FCB technology and privatization of the two public transport companies to improve their operational and economic efficiencies. Other recommendations were:

- reform of the energy pricing scheme to remove current distortions
- imposition of more stringent vehicle emissions standards to promote cleaner fuel-cell technology
- consideration of a carbon tax to promote zero-emission FCBs
- reduction or elimination of import duties on fuel-cell-related components
- government support for R&D on H<sub>2</sub> technology
- establishment of codes and standards for safe hydrogen operations.

*Making choices about hydrogen: Why Egypt declined to participate in the GEF FCB demonstration project*

Recently the government of Egypt decided to withdraw from the GEF FCB programme. Three main reasons lay behind that decision.

First was the recommendation from the GEF to wait. One of the main implementation strategies of the GEF's FCB programme is project phasing for structured learning, where FCB projects under way provide lessons learned to those beginning implementation at a later time. A key lesson learned concerns the procurement of FCBs, and specifically the validation of the FCB programme's strategic assumption that FCBs can be procured competitively. To this end, the Egypt and India FCB projects were advised by the UNDP, with the guidance of the GEF secretariat and the support of the GEF council, to wait for the Brazil, China and Mexico FCB projects to advance sufficiently such that the procurement-related assumption could be validated (Global Environment Facility, 2004).

Second was the recognition that the project was focused on a single-technology-driven approach without an integrated strategy. The GEF's FCB project involved the demonstration of a single technology that was in the early stages of maturity. Focusing on a single technology would not address the many problems of the transport sector in Egypt, outlined earlier. There has been growing recognition of the need for a more holistic approach to secure a sustainable path for Egypt's transport sector.

Third was the need to allow more time for the commercialization of CNG. While the FCB project was being developed, government support led to the successful commercialization of CNG technology (as mentioned above). Today Egypt ranks eighth worldwide in the use of CNG as a transport fuel. The risks associated with the new FCB technology, the high capital costs needed and the lack of infrastructure, together with the other barriers identified above, made it difficult for the government of Egypt to proceed with the GEF project. For a developing country like Egypt it appeared to be too early and too costly to start a demonstration of FCB technology. It might be more rational to allow more time for the successful CNG technology to penetrate further in the transport sector in Egypt, while developing a more integrated strategy to achieve a sustainable transport system.

## Rethinking sustainable transport

While several studies have been conducted and sound strategies and plans have been developed to address the challenges faced by the Egyptian transport sector, the implementation of these plans has suffered from different barriers.

- Lack of intersectoral coordination (harmonization of policies, institutional cooperation) and limited institutional capacity to adopt, implement and further develop the programmes effectively.
- Focus on single infrastructure investments or technology-driven approaches without an integrated view of broader requirements for successful intervention.
- Pressing needs to find solutions to pending day-to-day problems at the cost of adequately addressing the long-term sustainable development needs of the transport sector.
- Possible public perception, social and cultural barriers and occasionally conflicting interest between the different key stakeholders.
- Limited access to suitable financing mechanisms to meet the required investments needs.
- Inadequate emphasis on integrating sustainable transport planning with urban planning of new cities, and on promotion of non-motorized transport in middle-size provincial cities.

To address these challenges, a recent initiative also supported by the GEF is being developed to realize a long-term sustainable transport sector in Egypt. The objective of the new initiative is to reduce the growth of energy consumption and the related GHG emissions of the transport sector, while simultaneously mitigating the local environmental and other problems of increasing traffic, such as deteriorated urban air quality and congestion (UNDP, 2005).

This project takes a broader perspective on ways to reduce the growth rate of energy consumption in the transport sector and facilitate market development towards “sustainable mobility”. It does so by supporting the key stakeholders in Egypt to:

- reduce the growth of overall transport demand by improved land use and other urban planning measures, especially in new urban areas currently under development
- maintain or increase the modal share of sustainable public transport and reduce the use of private cars and other low-capacity motorized transport for regular daily commuting
- maintain or increase the modal share of non-motorized transport, with a focus on provincial medium-sized cities
- improve the energy efficiency and logistics of freight transportation by promoting a modal shift from road to rail and inland waterways and promoting measures towards optimizing the cargo transport system and vehicles used for that purpose in general.

The past experiences from other countries suggest that in order to deal effectively with the transport sector problems, there is a need for a holistic approach combining a package of different measures at different levels, rather than trying to address the challenges faced with any single-technology or non-technology-driven intervention. As of today, this project is still in its early stages of development.

## Conclusions

Road is the dominant mode of transport in Egypt, in both passenger and freight operations. Thus the transport sector is a major consumer of fossil fuels and therefore contributes a significant share of the country’s emissions of air pollutants and GHGs.

Transport problems are particularly acute in the Cairo metropolitan area, one of the world’s megacities with a population of more than 17 million. Air quality measurements in Cairo reveal high levels of pollutants that exceed both national and WHO standards. GHG mitigation options for the transport sector outlined in Egypt’s first national communication to the UNFCCC included a number of policies and measures, some of which have been highly successful – such as improved energy efficiency through vehicle maintenance and tuning-up of vehicle engines, phasing out of leaded gasoline and a programme to encourage the use of CNG as a vehicle fuel. Others, such as the reintroduction of electrified railways in intercity and intra-city transport, intensifying the use of environmentally sound river transport systems, extending underground metro lines to newly developed cities and testing electric and hybrid buses, are in need of further development.

Although in some areas, such as the production of H<sub>2</sub> and the manufacture of buses, Egypt has strong capabilities to support the implementation of a fuel-cell bus demonstration project in Cairo, a feasibility study identified a number of barriers that could hinder the commercialization of FCB technology. These barriers included extremely high capital investment, technology uncertainties, shortages of qualified human resources, safety issues, public acceptance of H<sub>2</sub> as a fuel and a lack of a proper regulatory framework and infrastructure.

In 2003 the Egyptian government decided to withdraw from the GEF-sponsored fuel-cell programme. Many reasons lay behind that decision, but among the most important were a recommendation from the UNDP-GEF to wait until similar projects in China and Brazil had gained some experience, the absence of a holistic approach going beyond the focus on a single technology that is in its early stages of development and the need to give time for the successful CNG commercialization programme that is under way.

It was thus viewed as too early and too costly for a developing country like Egypt to start a demonstration of the FCB technology at this stage. Instead, a new initiative has just started to develop an integrated plan to realize a long-term sustainable transport sector in Egypt. The objective of the new initiative is to reduce the growth of energy consumption and the related greenhouse gas emissions of the transport sector, while simultaneously mitigating the local environmental and other problems of increasing traffic, such as deteriorated urban air quality and congestion.

## Notes

1. The main categories of goods transported in Egypt are petroleum products; food and agricultural products; construction materials; and manufactured goods (including wood and metal products). The transport of imports and exports via Egyptian ports, the transport of agricultural products and the transport of cement from factories to ports for export and to local consumers present the main transport markets.
2. Although the conversion kits are now imported, there are plans to manufacture them locally. The CNG is produced locally by many companies.
3. Not all of these are totally state-owned; some are owned by multinational oil companies such as BP and Shell.

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## 9

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## Practical pathways towards a “hydrogen economy”: A view from Iceland

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*Ágúst Valfell*

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### Introduction

In recent years Iceland has been mentioned as a possible candidate to implement a “hydrogen economy” based on renewable energy. Quite a bit of attention has been given to Icelandic efforts in this area, and some media reports have been very effusive about the prospects for hydrogen as the final piece in the puzzle to implement a completely sustainable energy sector.

According to Ragnarsson and Helgason (2003), over 70 per cent of all primary energy used in Iceland comes from sustainable energy sources. Nearly all energy for stationary use is provided by either geothermal or hydropower sources. The nearly 30 per cent of primary energy that is not from renewable sources comes almost entirely from oil and gasoline. The use of coal and gas as energy sources is negligible.

Annual oil use is currently around 850,000 tonnes and is, roughly speaking, distributed equally between air transport, fishing operations and other mobile surface use (freight, transport and heavy machinery).

Annual greenhouse gas emissions that are counted towards the Kyoto “quota” are somewhat greater than 3 million tonnes of CO<sub>2</sub> equivalent. Over 50 per cent of these emissions stem from oil use. The target for annual emissions in the period 2008–2012 is that they should not exceed 3.6 million tonnes of CO<sub>2</sub> equivalent. It is estimated that Iceland will readily meet this target due to the 10 per cent increase in GHG emissions from 1990 levels allowed because of the country’s early and large-scale adoption of low-emission renewable energy sources, and due to Decision 14/

CP.7 of the Kyoto Protocol that exempts process-based CO<sub>2</sub> emissions from aluminium smelters from being counted towards total emissions under certain extenuating circumstances. Nonetheless, the government aims to take a proactive stance to reduce GHG emissions further, primarily through consultation with the aluminium industry to ensure minimal PFC emissions from smelters, changes in tariffs and incentives to promote use of more fuel-efficient vehicles, reduction of organic waste disposal, collection of landfill gas for energy recovery and encouraging the fishing industry to increase efficiency.

It has been estimated, using current economic, environmental and technical criteria, that Iceland has the potential for generating 50 TWh/annum of electricity from hydropower and geothermal sources. The potential of hydropower is assumed to be 26 TWh/a, while that of geothermal energy is assumed to be 23 TWh/a. Currently about 8.5 TWh/a of electricity is being generated, so there is plenty of room for growth. Also it is quite possible that the potential for electrical generation via geothermal energy is much greater, due to the fact that the estimate for geothermal power was fairly cautious and, perhaps more importantly, due to technological advancements that might open possibilities for harnessing a considerably greater portion of geothermal energy for electrical generation (by an order of magnitude, according to the most optimistic accounts, e.g. Friðleifsson and Elders, 2005).

Iceland thus has ready access to substantial amounts of reasonably priced renewable energy. The problem is that the country is far removed from major markets, and utilizing this energy has not always been straightforward.

Currently about two-thirds of the electricity generated in Iceland is used by heavy industry. Aluminium production constitutes by far the greatest part of this use, and is growing rapidly. There is, however, an interest in diversifying the large-scale uses of electricity.

A possibility for addressing the problems of fuel supply, greenhouse gas emissions and diversification of the demand side of the energy sector would be large-scale production of alternative fuels for mobile use. There are two main possibilities here, electricity and hydrogen (Óskarsdóttir et al., 2005).

This chapter will focus on hydrogen in the Icelandic energy sector, and try to relate developments and needs in Iceland to those in a wider world.

## Possible roles for hydrogen in Iceland

Hydrogen is an energy carrier, like electricity, and generally not an energy source, in the sense that there are hardly any “hydrogen wells” to be found (there are some examples of natural hydrogen sources such as

geothermal vents, but they are minor). In this respect hydrogen differs sharply from oil and natural gas.

Hydrogen is most commonly produced by reacting steam with natural gas. This has generally been the least expensive method, but a lot of carbon dioxide is produced as a by-product, as well as some carbon monoxide. Electrolysis is another traditional method of making hydrogen. Electrolysis produces very pure hydrogen and, depending on the energy source for the electricity, can involve minimal greenhouse gas emissions.

Hydrogen has been produced via electrolysis in Iceland since 1952, when domestic production of synthetic fertilizer began. Fertilizer production in Iceland has recently been discontinued, but there is currently some hydrogen production for vehicular use.

Currently, plans for hydrogen production are mostly oriented towards direct use of hydrogen as an energy carrier to replace gasoline and diesel oil in surface transport. Automobile applications for hydrogen have been in the forefront, but marine applications are also of great interest due to the importance of the fishing industry in Iceland. Storage of hydrogen poses a particularly daunting challenge in this regard as large fishing vessels are very energy-intensive and must be able to stay at sea for long periods of time, refuelling infrequently.

Storage of hydrogen has been a major obstacle when it comes to mobile, energy-intensive applications. Due to its low energy per volume, hydrogen is not as convenient to use as oil or gasoline. Several means of improving the energy density have been investigated. Improvements in material technology have made high-pressure storage more attractive as an intermediate technology (though considerable energy is expended compressing the hydrogen), while liquefaction does not seem to be a feasible avenue due to energy losses and problems with prolonged storage. Solid-state storage of hydrogen has been investigated intensely and is promising, despite problems of price and kinetics.

The heavy seas of the North Atlantic put great demands upon the reliability of a ship's power plant. It is thus likely that any use of hydrogen for large-scale marine applications would either be indirect, with hydrogen as an ingredient in a synthetic fuel used by the ship, or would involve solid-state storage of hydrogen. It should also be noted that the large diesel engines in ships used in Iceland are much more efficient than the combustion engines in passenger vehicles, so the advantage in fuel efficiency gained by switching from a gasoline engine to a hydrogen fuel cell in a car will not be nearly as significant aboard ship. Thus the increased costs of using hydrogen are not offset by increased efficiency in the same manner as in cars, and the economics of converting to hydrogen are less attractive.

A popular idea is to use hydrogen as an energy storage medium for intermittent renewable energy sources such as wind or solar power. The

idea is to use electrical power generated in excess of that supplied to the grid at any given moment to produce hydrogen via electrolysis, and then produce electricity from the hydrogen, using either fuel cells or combustion-based generators, when there is a need for more electricity at a later time. In this case, hydrogen storage would not pose a problem since space is usually not as restrictive in stationary applications. This scenario for energy storage is mostly confined to areas that are not connected to a large electrical grid and could absorb excess electricity from intermittent sources. Since reservoir-based hydropower plays such a large role in generating electricity in Iceland, it is easier to accommodate other fluctuating sources of electrical energy than if other baseline power sources were predominant. It should also be noted that the energy efficiency of the conversion electricity-hydrogen-electricity is not particularly attractive.

So far this chapter has mostly been looking at pure hydrogen as an energy carrier, but there are other indirect means for using hydrogen as well. Although synthetic fuels, such as Fischer-Tropsch diesel and methanol, are generally produced from coal and natural gas, there is an alternative approach that has been considered in Iceland: using the emissions from aluminium smelters and other heavy industry as a relatively concentrated source of CO<sub>2</sub> and CO that could then be reacted with hydrogen to produce synthetic hydrocarbon fuels (Arnason and Sigfusson, 1999). The value of this approach is that synthetic fuels produced in this fashion would be carbon-neutral in emissions. Also, such fuels are more easily handled than pure hydrogen, so it might be possible to sidestep some of the technical issues that make the use of hydrogen for mobile applications tricky. Here, as in the other options, price is an issue.

Many experts are of the opinion that the first widespread use of hydrogen as an energy carrier will be for consumer electronics. Cellphones, laptop computers and music players use comparatively little energy, but consumers are willing to pay a premium for them to have extended periods between recharging (e.g. a laptop should be able to run continuously during a long airplane flight). It is quite reasonable to expect that there would be some domestic production of hydrogen for recharging these devices, but this would not call for any substantial increase in energy production as the amount of energy used is small compared to that needed for transport, and also since hydrogen would be replacing rechargeable batteries that are already getting energy from the grid.

In some ways Iceland's energy resources may be considered to be "stranded", in the sense that there is no electrical connection to a major market. However, energy is exported indirectly in the form of aluminium and other products of energy-intensive industry. Some preliminary studies have been carried out on the possibility of exporting energy in the form of hydrogen, by either ship or underwater pipeline. First indications

are that it would be much more suitable either to export energy in the form of a product (i.e. aluminium or via greenhouse farming) or as electricity via a submarine cable rather than exporting hydrogen. One should also keep in mind that Icelandic energy sources, though large in per capita terms, are not very large in absolute terms (50 TWh of electricity is only enough to meet the needs of roughly 6 million average OECD citizens).

## Creating an environment for change

In 1997 Iceland's Ministry of Energy appointed a committee to look into opportunities for domestic fuel production. In its report, the committee recommended that efforts be directed towards hydrogen and related fuels as one means to reduce consumption of imported oil. Two years later a corporation, Icelandic New Energy (INE), was formed. Fifty-one per cent of the shares in INE are held by a holding company whose shareholders are a consortium of Icelandic business firms, research and education institutes and the Iceland government. Forty-nine per cent of the shares are held by DaimlerChrysler, Norsk Hydro and Shell Hydro (Skulason and Bjarnason, 2003).

The key project undertaken by INE is a fuel-cell bus and refuelling station demonstration project, the Ecological City Transport System (ECTOS), financed by the European Union under its Fifth Framework Programme. The ECTOS project (2001–2005) provided an example of a working, commercial refuelling station located in an urban area, the capital city of Reykjavik, and a demonstration of three fuel-cell buses. It opened in April 2003 and is operated by INE in collaboration with Shell Iceland. The station, equipped with a Norsk Hydro alkaline electrolyser, produces hydrogen on site using renewable electricity provided by the municipal power grid to split water into hydrogen and oxygen. The station is equipped with a compressor unit that delivers gaseous hydrogen at 440 bars to storage bottles (Skulason and Bjarnason, 2003) and “a dispenser capable of delivering about 30 kg of Hydrogen in less than 7 minutes (a benchmark for bus-refuelling)” (Sigfusson, 2005). In its initial stage the station could provide about 120 kg of hydrogen a day.

The ECTOS project is now completed and the station is still open. Initial results show that public acceptance of hydrogen buses was high and the general experience of both drivers and passengers was positive. However, maintenance costs were higher and fuel efficiency lower than had been anticipated. The buses proved to be safe and were operated without major incident. But the results for public acceptance are somewhat questionable, in this author's opinion, since the public were not made aware

of the realistic energy efficiency of the hydrogen buses and issues of price. Customer satisfaction is not an indicator of economic sense, especially when the customers are not paying the full price for the service. However, studies of public acceptance with regards to safety concerns, bus performance, etc. are quite valid. The results of the ECTOS project have been used for infrastructure studies as well as by makers of equipment, e.g. Norsk Hydro and Daimler (Skulason, 2006).

There are also some smaller-scale projects concerning H<sub>2</sub> use aboard ships, infrastructure studies and hydrogen storage. According to a report by the Icelandic Ministry of Industry and Commerce in July 2006, the Icelandic government intends to support hydrogen research further and partake in international cooperation towards a “hydrogen society”. It is assumed that this will mainly be done via further demonstration projects geared towards cars and marine applications of hydrogen. The impetus for this is to ensure that the nascent hydrogen research community in Iceland maintains momentum.

Attention now turns towards how to go about advancing the use of hydrogen as an energy carrier in a country such as Iceland. Most importantly, one must bear in mind that hydrogen is a means towards an end, not an end in itself. This is a distinction that it is vital to make, especially on the government level, and is especially true for smaller countries with limited resources which might be tempted to place undue emphasis on a single area. A private concern involved in hydrogen technology might be inclined to advance the use of hydrogen for its own sake, but that would probably not be conducive to long-term business success. In this respect, it is important to define specific objectives (i.e. reduced greenhouse gas emissions, security of fuel supply or new forms of energy storage) so that the capacity of hydrogen for reaching those goals can be assessed and effective action can be undertaken.

There is often a tendency for governments to write legislation in a fashion that assumes a given state of technology, thus prescribing rules and regulations dealing with a certain technical approach rather than a more results-oriented approach. An example of this is Icelandic tariff regulations regarding the import of vehicles (2005). These regulations state that when importing a vehicle with an engine size less than or equal to two litres the tariff is 30 per cent, whereas it is 45 per cent if the engine size is greater than two litres. There are plentiful examples of either diesel or hybrid vehicles with engine sizes greater than two litres that have lower fuel consumption than vehicles, comparable in size and performance, with engines smaller than two litres. Thus there is an incentive for consumers to buy the less efficient vehicle – in contrast to the aim of the law. A much more direct (results-oriented) approach would be to scale the tariff to the nominal fuel efficiency of the vehicles, which is

measured in a standard fashion for all newer cars. This tendency towards means-oriented legislation is understandable in many ways; for instance when safety standards are introduced there is a desire to ensure a uniformity of approach to the rules. However, such laws often have the detrimental effect of discouraging new technological solutions because the new technology had not been anticipated when the rules were written. Often the legal hurdles are too many and too great for the new technology to gain market entry. This applies not only to safety issues, but to a host of other aspects as well. Although Iceland is used as an example, this is hardly a uniquely Icelandic problem.

This brings us to the first prescription for introducing a new technology such as hydrogen for widespread energy use: carefully crafted laws and a reasonably responsive bureaucracy. This is probably one of the more difficult conditions to insist upon, but is an extremely important one. One factor in the rapid construction of the hydrogen filling station in Reykjavík was the willingness of local safety authorities to consider this unfamiliar technology in a quick manner, which can be contrasted with a more plodding official response in larger societies.

The next issue is that of research and development. Depending on what role hydrogen is to play in the energy sector, there is the matter of which technology is readily accessible and what countries lacking a large industrial or research capacity can do to improve their condition. For instance, Icelandic interest is mainly in the use of domestically produced hydrogen as an energy carrier for automobiles. However, the automobile industry is based on mass manufacturing. Icelandic consumers have no influence on this industry, and it is quite unlikely that Icelandic research will have any direct influence in this area. Thus one cannot anticipate that Iceland will have any direct effect upon the emergence of hydrogen vehicles for the consumer market.

However, this does not mean that a small society such as Iceland should not invest in research and development in the area of hydrogen. Rather, the hydrogen effort should be included in a more broad-ranging effort to reach the goals that hydrogen technology is meant to strive for. For instance, it is necessary to conduct research on infrastructure improvements, hydrogen production possibilities and some basic hydrogen-related research to train engineers and scientists and improve their competence. In short, the practical research effort in smaller countries must be oriented towards niche competencies and local expertise, and address questions that will not be answered by foreign parties.

The success of a new technology hinges upon public acceptance. This can be on two scales. First of all users must find the new technology easy to use, fairly priced and convenient. On another scale the public as a whole must feel confident in the new technology, particularly concern-

ing safety and effects on the environment. Therefore it is necessary to educate the public in a clear and concise manner, stating both the pros and the cons. For hydrogen, a commonly cited public concern is safety. Images of the *Hindenburg* accident tend to occupy people’s minds, and some are confused as to whether there is any relation to hydrogen bombs. Demonstration projects and an emphasis on the positive aspects of hydrogen in Iceland seem to have alleviated fears the public might have had, and there is a fairly favourable view of hydrogen as an energy carrier. It is important that the possibilities of hydrogen should not be overstated, and that the public should not be led to believe that a hydrogen economy is “just around the corner”. This could have adverse long-term effects on the credibility of hydrogen researchers and possibly lead to waning interest in hydrogen as an energy carrier.

Converting to a full-fledged “hydrogen economy” calls for a substantial change in infrastructure, and this can lead to a “chicken-and-egg” problem for the market. For instance, it would be difficult for automobile sellers to introduce hydrogen vehicles if there is no pre-existing system of filling stations to refuel them. Similarly, it is not appealing to energy vendors to build hydrogen filling stations if there are no customers. To solve this dilemma there are a few approaches, two of which will be mentioned here. One idea is that the government builds a number of filling stations, thereby guaranteeing that automobile owners have ready access to fuel in most areas. Another idea is that the government pledges to buy and operate a significant number of vehicles, thus creating a customer base for energy vendors, which would then build up an infrastructure. One might also envision some mix of these two strategies.

It should be stressed once more that conversion to a “hydrogen economy” is not an end in itself, but a possible means towards an end – and that endpoint will vary from region to region. There will also be competing technologies aimed at reaching many of the same goals as hydrogen. For instance, in Iceland the use of hydrogen as a means of storing energy from intermittent sources will probably not be expedient. This is due to the large amount of unutilized, steady and renewable energy sources that are cheaper to use than the intermittent ones, and the fact that it will probably be less costly and more efficient to use wind energy to pump water into existing reservoirs, rather than using it to produce hydrogen for energy storage. Similarly hybrid electric automobiles, with the ability to be recharged from an outlet overnight, may prove to be successful, competing with pure fuel-cell cars. This technology is receiving increased attention due to the much higher efficiency of the pathway from primary power to battery to motive power compared to the hydrogen route. It is especially important for nations with limited resources, which are intimately tied to technological development elsewhere, not to

commit to a single approach to solving their energy or environmental problems, but rather to adopt a policy of informed anticipation based on knowledge of several viable proposed solutions. Also, it should be stressed that there are usually a number of straightforward practical solutions that will help alleviate most of the energy and environmental issues that hydrogen technology promises to address. These existing opportunities for improvement should be carried out immediately, rather than neglected in the hope that a future cure-all will present itself.

## Conclusion

Hydrogen offers the tantalizing possibility of a clean energy carrier produced by a much broader range of suppliers than oil today. This promise of a clean and secure source of “fuel” has in recent years received increasing attention, and a great deal of research and development has been carried out to advance the cause.

This has been particularly notable where hydrogen has received a lot of political support, and there is long-standing interest in using Iceland’s plentiful renewable energy resources to produce an alternative energy carrier to replace oil. This builds on Iceland’s previous success in replacing fossil fuels for stationary applications such as generating heat and electricity. Although Iceland cannot launch a “hydrogen economy” on its own, it could become one of the earliest adopters of such an economy when the technology becomes available. Many of the issues addressed by Icelanders in their quest to reduce oil dependence and greenhouse gas emissions may be useful to other nations as well, particularly to smaller countries or those with limited industrial resources.

Hydrogen must be considered in a framework with other possible solutions to the energy and environmental issues that hydrogen is meant to address. Clear goals should be defined with regard to these issues.

Legal obstacles, such as prohibitive safety codes towards the adoption of new technologies, should be reduced. Laws and regulations should concern results rather than methods, and the civil service should try to deal rapidly and responsibly with new, unfamiliar technology such as hydrogen technology.

Research should be weighted towards niche areas or areas where local expertise is most likely to make a significant contribution. Low-cost basic research should be encouraged to train students and professionals to become familiar with hydrogen and hydrogen systems. Here, flexibility is also important.

The public should be informed in an unbiased manner about the pros and cons of hydrogen technology (and competing technologies), safety is-

sues, likely cost and availability. If technological development can make the relevant hydrogen technology available at a competitive price (or is anticipated to do so in the near future), governments will most likely have to step in to solve the “chicken-and-egg” problem of introducing demand for and supply of hydrogen simultaneously.

Authorities should not take a narrow view of hydrogen, but consider competing technologies as well, aiming to facilitate the adoption of the best available technology progressively.

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## Part III

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# Hydrogen fuel cells and the global automobile industry

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# Introduction

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For many decades the automobile sector was regarded as a mature industry within which technological changes were incremental and competitive practices were long established. Among the first challenges to these traditional habits and practices was the introduction of small cars by emerging Japanese automobile exporters. A second came from the growing awareness that motor vehicles were an important contributor to rising levels of urban pollution. The third was the oil shock of 1973, which briefly drew attention to the issues of energy security and fuel efficiency.

But none of these challenges significantly or durably changed competitive practices among the vertically integrated motor vehicle companies that dominated the industry. More powerful cars, SUVs<sup>1</sup> for example, recaptured the focus of attention and the catalytic converter, an end-of-pipe approach rather than a more substantive innovation, became the solution of choice for the automobile emissions problem.

These consumption models and this technological approach diffused to developing countries as private automobile ownership spread and market opening processes created new opportunities for globalized production. Foreign direct investment and joint ventures with local firms established motor vehicle assembly and production in many developing countries. Mergers and acquisitions led to increased concentration in the auto industry globally and enabled automobile manufacturers to position themselves across a wide spectrum of end markets, from luxury to compact vehicles. Partnerships with preferred “first-tier” suppliers were formed for

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*Making choices about hydrogen: Transport issues for developing countries, Mytelka and Boyle (eds), United Nations University Press, 2008, ISBN 978-92-808-1155-1*

the purpose of sharing the risks and costs of designing principal components and subsystems. By reducing the number of suppliers, distinct components and parts, these partnerships have accelerated the pace at which new products are designed. Shared platforms, modularized production, long-term contracts with a global scope and the accommodation of first-tier suppliers within the assembler's own factory or near to it have reduced the costs and uncertainties associated with a process of continuous change in the motor vehicle industry.

Towards the end of the millennium, rising fuel prices and pollution levels drew attention to the need for more innovative solutions to the problems of energy security, fuel efficiency and high levels of greenhouse gases, but policy support for a concerted move towards clean fuels and alternatives to the internal-combustion engine (ICE) was neither strong nor sustained, as changes in the 1990 California Air Resources Board zero-emission-vehicle targets illustrated (Yarime, Shiroyama and Kuroki). This added to the difficulties that General Motors encountered in commercializing an electric vehicle, although only a few years later Toyota would successfully introduce the first hybrid car, the Prius, into the American market. Two factors were particularly important in explaining the speed of its adoption: it catered to traditional tastes for power and range by keeping the ICE at the core; and it enhanced fuel efficiency through the introduction of an electric battery that could take over for stop-and-start urban driving. The battery, moreover, was recharged through regenerative braking.

But these technological innovations alone would not have generated the strong commercial response that followed; governments in a number of large-market countries provided demand-side incentives by subsidizing the difference in price between the more expensive hybrid and a similar ICE vehicle. The Toyota Prius now has many imitators, and even models such as "gas-guzzling" SUVs and large luxury cars are being produced in hybrid versions, thus contributing to the maintenance of traditional consumption patterns.

The wide array of technological choices is raising new issues for developing countries in their role as both importers and producers of automobiles and auto parts. Growing numbers of used-car imports, for example, present a major problem for technological catch-up in developing countries. They prolong the life of older, less energy-efficient technology and slow down the need for local micro and small enterprises, engaged in auto repair, to upgrade their skills. Skill upgrading is needed to service the electric-based systems of contemporary hybrid vehicles – which are similar to those that will be used in wholly electric and fuel-cell vehicles of the future. Skill upgrading is also needed to deal with the growing

importance of numeracy associated with electronic controls, especially those used in the fuel-injection systems that are critical components in flex-fuel engines and enable drivers to switch easily between 100 per cent ethanol, 100 per cent gasoline or any blend of the two. Flex-fuel engines that will make it possible to switch between compressed natural gas (CNG), gasoline and ethanol, and others that will enable the use of a wide variety of inputs for biodiesel, are now under development. In the short and medium term, making and maintaining such engines will be important elements in a strategy to reduce energy costs and pollution levels in the megacities that have emerged in the developing world. Imports of used cars, however, create a disincentive to invest in such capacity building.

In addition to their role as growing consumers of imported motor vehicles, many developing countries are also active players in both the manufacture and the export of motor vehicles and auto parts. More than two dozen developing countries currently make and export automobiles, buses and/or parts and components.<sup>2</sup> The importance of the motor vehicle industry in stimulating demand for inputs from a wide range of upstream industries, including steel, plastics, new materials, glass and electronic and electrical industries, has made the automobile sector one of the driving forces in industrial employment and growth in all the principal global players today. Governments in many developing countries have thus promoted the automotive industry in their overall development strategies.

Most of the subsidiaries and joint-venture companies of multinational corporations, whether located in Canada (Molot) or in developing countries, simply reproduce models and production processes developed in their parent firms. Even wholly owned national firms have largely pursued an imitative strategy that has yet to respond to the emergence of new technologies by building capacity in flex-fuel engines or electric vehicles, as the case of Malaysia illustrates (Kari and Rasiah).

There is some evidence, however, that three of the developing world's largest countries have begun to explore a variety of innovative alternatives to the issues of energy security, fuel efficiency and urban pollution. Brazil (Part II) has worked upstream to develop biofuels and produce flex-fuel engines. India (Part II) has converted buses in its capital city to CNG, and its largest automotive company, Tata Motors, has launched a new, small, cheap and more energy-efficient family car, the Nano. In China (Part IV) local automobile companies and joint-venture firms are building electric and hydrogen fuel-cell vehicle prototypes. Learning more about these experiences can help in choosing among pathways that better position developing countries for the technological changes ahead.

## Notes

1. Sport utility vehicles.
2. This includes the well-known large-market participants in this global industry, China, Mexico and Brazil, as well as a number of lesser-known producers and in some cases exporters of automobiles, trucks, auto parts and components, such as Argentina, India, Indonesia, Malaysia, Nigeria, Thailand and South Africa.

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# The strategies of the Japanese auto industry in developing hybrid and fuel-cell vehicles

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*Masaru Yarime, Hideaki Shiroyama and Yusuke Kuroki*

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### Introduction

Currently it is an urgent issue at the global level to reduce the amount of pollutants in the atmosphere. In areas where the atmospheric concentrations of nitrogen oxides (NO<sub>x</sub>) and suspended particulate materials are high, automobiles are regarded as the main source of these substances in many cases. Therefore, environmental regulations have been imposed on exhaust gases of automobiles in the past in many parts of the world, with the aim of encouraging innovation in the auto industry.

At the beginning of the 1970s the most stringent regulation in the world, the so-called Muskie Act, was enacted in the United States. Under this Act, the auto industry was required to reduce the amount of emissions of carbon monoxide (CO), hydrocarbons (HCs) and NO<sub>x</sub> to one-tenth. As this target was considered by the auto industry to be unrealistically stringent without any sound technical basis, the Muskie Act was opposed by the US auto industry so fiercely that the Environmental Protection Agency (EPA) decided in 1973 to delay its implementation (Mizutani, 1990, 1991a, 1991b).

A year earlier the Environmental Agency in Japan had publicly announced that legislation similar to the Muskie Act would be introduced soon in the country. Japanese auto makers, having less influence on environmental policymaking than their counterparts in the United States, were thus obliged to concentrate on complying with the coming regulations through technological innovation (Wallace, 1995; Zhu and Otahara,

2004). Specialized in the production of motorcycles and relatively small-sized automobiles, Honda focused on utilizing its expertise in engines for technological development and became the first auto producer to succeed in complying with the stringent target of emissions reduction by developing a new type of engine, namely the CVCC. In contrast, larger companies such as Toyota and Nissan, which produced a full range of automobiles, sought to achieve the target by creating a new type of catalyst, the three-way catalyst, rather than changing the structure of engines. What is interesting to note is that although the CVCC engine was able to achieve the target for emission reduction from the beginning, Honda subsequently abandoned its production, whereas the three-way catalyst has improved significantly over time in reducing emissions and came to be adopted widely throughout the world. In effect, the CVCC engine turned out to be a transient technology.

Uncertainty and diversity are inherent in the process of technological change (Rosenberg, 1982, 1994). There are multiple options for clean vehicle technologies, including electric, hybrid and fuel-cell vehicles, with their long-term cost and performance very difficult to predict in advance. Furthermore, the strategies of companies are formed not just in terms of their market and competitive positioning, but also with reference to their histories and institutional environments (Levy, 2005). Among the most important institutional conditions influencing technological change in industry is environmental regulation (Yarime, 2007). Under the circumstances, a certain degree of heterogeneity can be observed with regard to corporate strategies on the development of alternative clean vehicles. The environmental regulations that were introduced in the United States in the 1990s had particularly significant impacts on the direction and speed of technological development at Japanese automotive producers, which relied heavily on the large US market for their exports.

This chapter examines how environmental regulations have influenced the strategies of the Japanese auto industry in developing alternative clean automobiles, with a particular focus on hybrid and fuel-cell vehicles. The extent to which Japan's leading auto producers are moving towards commercializing clean vehicles is having a worldwide impact on the automobile industry, shifting the technological trajectory on clean vehicles and transforming the industrial structure through inter-firm alliances. In particular, hybrid vehicles are quite distinct from conventional gasoline vehicles, in that their technology critically depends on the performance of batteries, motors, inverters and control systems, which are also crucial components of fuel-cell vehicles. Therefore, it is becoming increasingly critical to establish close relationships between car manufacturers and component producers for successful development and commercialization of alternative clean vehicles. This will have significant

implications for corporate strategies and policymaking in developing countries which intend to promote the growth of this industry.

## Regulation for emission control in the auto industry in the 1990s

In the United States the California Air Resources Board (CARB) enacted a low-emission vehicle (LEV) regulation in 1990. The LEV regulation required that seven large automobile producers, namely the Big Three (General Motors, Ford and Chrysler), plus Toyota, Nissan, Honda and Mazda, include zero-emission vehicles (ZEVs – vehicles that do not emit any pollutants) as a small percentage of their total sales. The initial targets for the introduction of ZEVs were set at 2 per cent after 1998, 5 per cent after 2001 and 10 per cent after 2003. This invited fierce opposition from the auto industry, which argued that discussions with regard to the introduction of the regulation did not reflect their understanding at the time that alternatives to the conventional gasoline engine vehicle still presented many difficulties in technology and infrastructure. Despite that strong resistance, the ZEV regulation was enacted in the end. The necessity to comply with the regulation greatly prompted the auto makers to develop ZEVs.

Since at that time no feasible options were considered to be available for ZEVs other than electric vehicles, automobile manufacturers focused their efforts on developing this technology. It became increasingly clear, however, that there were serious difficulties with electric vehicles, notably the poor performance of the battery and a short cruising range (Sato, 1999). As it was expected to take much more time than planned for these vehicles to replace conventional gasoline vehicles, a consensus soon formed in the industry that it would be impossible for sales of ZEVs to reach 2 per cent of total vehicle sales by 1998. Auto makers thus strongly argued to CARB that a full-scale introduction of electric vehicles would face serious difficulties from a technical perspective. Furthermore, the US auto industry, which had traditionally derived most of its profits from larger vehicles, light trucks and more recently sport utility vehicles, was particularly concerned about low expectations of market viability for LEVs (Levy and Rothenberg, 2002).

The auto industry's aggressive lobbying worked well, and consequently CARB decided in 1996 to revise the ZEV regulation. The implementation of the ZEV mandate was delayed for five years; that is, the targets for 1998 and 2001 were cancelled, but the mandate that ZEVs constitute 10 per cent of total sales in 2003 was kept unchanged. And the big seven companies were also required to carry out fleet demonstration projects

of ZEVs from 1998 to 2000 through a memorandum of agreement with CARB. As the industry continued to lobby further, CARB subsequently came to recognize other vehicles whose burden on the environment is very small, but not nil like ZEVs. When the regulatory framework was revised in 1999, the category of partially zero-emission vehicles (PZEVs) and a multi-credit system were introduced, while the mandatory introduction of ZEVs by 2003 was maintained. In the new system a PZEV was regarded as equivalent to 0.2 ZEV, and it became possible to achieve the ZEV target by introducing ZEVs for 4 per cent and PZEVs for 6 per cent of the total sales.

In 2001 the regulation was amended again, and the category of advanced-technology PZEVs (AT-PZEVs) was newly established, to be equivalent to 0.4 ZEVs. ZEVs now corresponded to electric vehicles and hydrogen fuel-cell vehicles, AT-PZEVs to hybrid vehicles and fuel-cell vehicles with fuel reforming and PZEVs to gasoline vehicles which could comply with the super-ultra-low-emission vehicle (SULEV) level that had been created in 1998 through the tightening of the LEV regulatory framework (Takagi, 2003). The modified regulatory standard made it possible to achieve the 10 per cent target by introducing ZEVs for 2 per cent, AT-PZEVs for 2 per cent and PZEVs for 6 per cent of the total sales.

Once again, auto makers argued that they had considerable difficulties in realizing the 2 per cent target for ZEVs. Consequently, the procedure for calculating the credits for ZEVs, AT-PZEVs and PZEVs was changed in 2003 so that the credits for vehicles such as hybrids were increased. What is of particular importance is that it became possible to substitute AT-PZEVs for ZEVs, on the condition that a minimum of 250 ZEVs per year would be produced by the auto makers as a whole.

In the meantime, fuel-cell technologies had progressed significantly. The possibility of commercializing fuel-cell vehicles began to be discussed seriously, which subsequently led to the creation of a new public-private collaborative venture, the California Fuel Cell Partnership (CFCP), in January 1999. The goals set by the CFCP were to demonstrate fuel-cell technology by operating and testing vehicles, to demonstrate alternative fuel infrastructure technology, to explore the path to commercialization and to increase public awareness (California Fuel Cell Partnership, 2004). The original eight members included a fuel-cell manufacturer (Ballard), automotive manufacturers (DaimlerChrysler and Ford), energy providers (BP, Shell Hydrogen and ChevronTexaco) and government agencies (CARB and the California Energy Commission). Honda, together with Volkswagen, joined the CFCP in October 1999, Nissan in March 2000, Hyundai and International Fuel Cells (now UTC Fuel Cells) in June 2000 and GM and Toyota in October 2000.

The CFCP sprang from the ZEV regulation initially, and was thus regarded as a driving experiment at the state level. As the technologies of fuel-cell vehicles improved substantially, however, the programme strengthened its nature as a national project, with subsequent participation by the Department of Energy and the Environmental Protection Agency. Since the world's major auto makers have joined, the CFCP has provided an arena in which each company could test new fuel-cell vehicles, and the driving standards of the programme function as milestones in the process of developing fuel-cell vehicles.

What one sees in California was basically the gradual regress of efforts to regulate pollution in the face of technological difficulties and the pressure of heavy lobbying, coupled with a sharp turn towards conservatism in the state. The stringent regulation requiring the production of ZEVs initially pushed the auto makers to conduct R&D on clean vehicles, particularly electric vehicles. As auto makers encountered technical difficulties, however, the regulation underwent a process of revisions which influenced the heterogeneous strategies the Japanese auto makers took in developing hybrid and fuel-cell vehicle technologies.

## The strategies of the Japanese auto industry

The strategies of Japanese auto companies in coping with environmental regulations are examined by using the Japanese patent data on clean vehicle technologies (Kuroki, 2004). The patent applicants considered in this study are six large Japanese auto makers: Toyota, Nissan, Honda, Mazda, Mitsubishi and Fuji Heavy Industries (Subaru). Patents are searched for technologies specifically related to electric vehicles, hybrid vehicles (series, parallel and series/parallel hybrid vehicles<sup>1</sup>) and fuel-cell vehicles, respectively, including components and control techniques. Patent data were obtained from the database maintained by the Japanese Patent Office.<sup>2</sup> Figure 10.1 gives the trends in patent applications made by the six Japanese auto producers for clean vehicles. Note that since the figure indicates the year in which each patent was published, its application was made 18 months earlier.

Applications for patents on electric vehicles appeared as early as the mid-1970s, when many auto makers in Japan were engaged in R&D. Throughout the 1980s, however, the number of patent applications for electric vehicles remained at a low level, as R&D on this technology was basically aborted at most of the auto makers, except the small firms of Suzuki and Daihatsu (Environmental Restoration and Conservation Agency of Japan, 2002). Following the introduction of the ZEV regulation in California in 1990, electric vehicles were again regarded as the

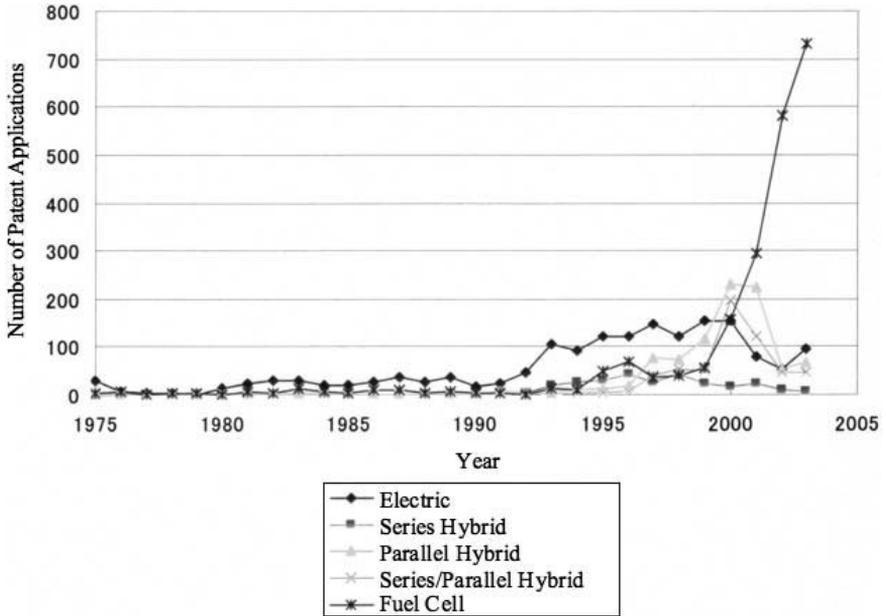


Figure 10.1 Patent applications by major Japanese auto makers on clean vehicles

main target for development, and the number of patent applications on electric vehicles began to rise sharply in the early 1990s. Applications stabilized at a level of a little more than 100 per year in the mid-1990s, after which they declined rather rapidly in the early 2000s.

This is considered to reflect the slow progress in the technologies related to electric vehicles. In particular, the performance of batteries is one of the most critical elements of electric vehicle technology, and there remained serious obstacles in improving it (Sato, 1999). At the beginning of the 1990s, electric vehicles with lead batteries were mainly developed, with many technical difficulties limiting the battery lifetime and the cruising range of vehicles. Consequently, the focus of R&D was shifted to nickel metal hydrate batteries and lithium ion batteries. Figure 10.2 shows the chronological development and commercialization of electric vehicles by the major auto companies, indicating that commercial production almost stopped in the early 2000s. Recently, however, major auto makers have announced that they plan to develop and commercialize plug-in electric vehicles, including those of the hybrid type which can utilize electricity stored at home (*The Economist*, 2006; Yamane, 2007). That could pave the way for a resurgence of electric vehicles in the future.

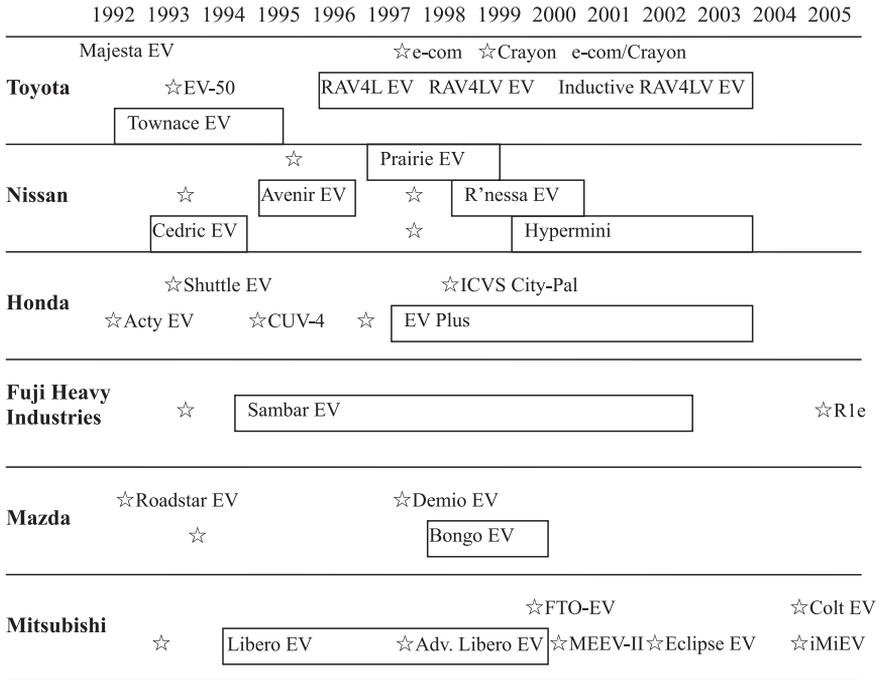


Figure 10.2 Development and commercialization of electric vehicles by major Japanese auto makers  
 Source: Center for Electric Vehicles (2006b), modified by the authors.

While the auto industry as a whole continued to lobby intensively against environmental regulations in the 1990s, the figures on patent applications suggest that several companies initiated technological development of hybrid vehicles. In particular, series hybrid vehicles, whose structure is very close to that of electric vehicles, were chosen initially to meet the development target. While patent applications on electric vehicles stagnated, those on series hybrid vehicles rose in the early 1990s. They began a gradual decline in the late 1990s, however, mainly due to a serious problem directly related to the structure of series hybrid vehicles. The efficiency of series hybrid vehicles was low, because the kinetic energy generated by the combustion engine is transformed into electric energy that is transformed once again into kinetic energy by the motor (Horie, 1999).

As the number of patent applications on series hybrid vehicles declined, applications on parallel hybrid vehicles, including series/parallel hybrid vehicles, began to increase in the late 1990s. Since the category of PZEV was created in the regulatory framework in 1999, it became

Table 10.1 Commercialization of hybrid vehicles by Japanese auto makers

Auto maker	Vehicle name	Year	Hybrid type	Hybrid system
Toyota	Prius	1997	Parallel	Toyota in-house (THS)
	Coaster Hybrid EV	1997	Series	Toyota in-house
	Crown Mild Hybrid	2001	Parallel	Toyota in-house (THS-M)
	Estima Hybrid	2001	Parallel	Toyota in-house (THS-C)
	Alphard Hybrid	2003	Parallel	Toyota in-house (THS-C)
	Prius	2003	Parallel	Toyota in-house (THS II)
	Harrier/Kluger Hybrid	2005	Parallel	Toyota in-house (THS II)
	Lexus	2006	Parallel	Toyota in-house (THS II)
	Camry	2006	Parallel	Toyota in-house (THS II)
Nissan	Tino Hybrid	2000	Parallel	Nissan in-house
	Altima Hybrid	2006	Parallel	Toyota (THS II)
Honda	Insight	1999	Parallel	Honda in-house (IMA)
	Civic Hybrid	2001	Parallel	Honda in-house (IMA)
	Accord Hybrid	2004	Parallel	Honda in-house (IMA)
Mazda	Tribute Hybrid	2004	Parallel	Aisin AW (HD-10)

*Source:* Toyota Motor Corporation (2003); Tachimoto, Hayashi and Kawabata (2005); Center for Electric Vehicles (2006c); Karishu and Tanokura (2007).

possible for auto makers to receive credits for ZEVs without actually producing pure ZEVs. That encouraged the auto manufacturers to shift their target of technological development to parallel hybrid vehicles, which were considered to be more feasible than other alternative technologies. The development and commercialization of hybrid vehicles by the major auto companies are given chronologically in table 10.1. Currently, most commercialized models of hybrid vehicles are of the parallel type.

With regard to fuel-cell vehicles, the auto makers basically started to apply for patents in the mid-1990s, and the number of applications increased sharply in the 2000s. That could also be considered to reflect the changes in regulations influencing the research focus in the auto industry. After the revisions of the ZEV regulation in 2001 and 2003, more ZEV credits were given to fuel-cell vehicles than to electric vehicles, and subsequently research activities started to be conducted intensively by major auto makers on fuel-cell vehicles. Initially these vehicles were mostly based on the reformation of methanol, because high-pressure hydrogen tanks were not yet well developed and it was considered that hydrogen-based fuel-cell vehicles could not have a sufficient cruising range (Nishimura, 2007). Since the early 2000s, however, the mainstream of R&D has shifted to the hydrogen type of vehicles, as it became clear that the reformation type of fuel cell takes a longer time to start up and has lower

energy efficiency than the hydrogen type. Table 10.2 shows the chronological development of fuel-cell vehicles by Japanese auto makers. Most types of vehicles developed so far are based on the fuel-cell/battery hybrid system, which suggests that the knowledge and experience accumulated through working on hybrid vehicles would be very important in developing fuel-cell vehicles.

This chapter has discussed the overall trends in patent applications for clean vehicles in the Japanese auto industry. As the chronological development and commercialization of electric, hybrid and fuel-cell vehicles suggest, however, there have been large differences in the R&D strategies among the major car makers in Japan, reflecting their own strengths and weaknesses as well as the environment surrounding them. Thus the chapter now examines the corporate strategies on R&D and inter-firm relationships in detail, using data on patent applications.

### *Toyota: Proactive approach with technological diversification*

The trends in Toyota's patent applications for clean vehicles are shown in figure 10.3. The arrows indicate when revisions and modifications were made to the ZEV regulation. The figure suggests that Toyota applied for patents on electric vehicles in the mid-1970s, after which it made very few patent applications from the late 1970s to the mid-1980s. The company started applying for patents on electric vehicles again in the late 1980s, when the ZEV regulation was discussed in California. Following the regulatory imposition, Toyota's patent applications jumped in the mid-1990s. The company released the first electric vehicle with nickel metal hydrate batteries, the RAV4L-EV, into the Japanese market in 1996. Figure 10.3 also indicates that Toyota began to apply for patents on series hybrid vehicles in the early 1990s, prior to the 1996 CARB decision to delay the implementation of the ZEV regulation. Patent applications for technologies related to parallel hybrid vehicles and series/parallel hybrid vehicles followed subsequently in the mid-1990s. Development of fuel-cell vehicles started in the same period, as the company's patent applications suggest.

In the 1970s the company had suffered badly from a negative image of being reluctant to act on environmental protection compared to Honda and Mazda, which were considered to be the leaders in developing technologies to reduce auto pollution. That experience became one of the major factors which later prompted the company to move actively into developing and commercializing clean vehicle technologies (Sasanouchi, 2000). As the ZEV regulation was imposed on the auto industry in the early 1990s, Toyota took various initiatives concerning environmental protection. In 1992 it set up an environmental committee chaired by the

Table 10.2 Development of fuel-cell vehicles by Japanese auto makers

Car maker	Vehicle name	Year	System	FC stack (power)	Fuel type
Toyota	RAV4 FCEV	1996	FC/battery hybrid	Toyota in-house (20 kW)	Hydrogen-absorbing metal alloy
	RAV4 FCEV	1997	FC/battery hybrid	Toyota in-house (25 kW)	Methanol reformation
	FCHV-3 (Kluger V)	2001	FC/battery hybrid	Toyota in-house (90 kW)	Methanol reformation
	FCHV-4 (Kluger V)	2001	FC/battery hybrid	Toyota in-house (90 kW)	High-pressure hydrogen (25 MPa)
	FCHV-5 (Kluger V)	2001	FC/battery hybrid	Toyota in-house (90 kW)	Gasoline reformation
	FCHV (Kluger V)	2002	FC/battery hybrid	Toyota in-house (90 kW)	High-pressure hydrogen (35 MPa)
	FCHV (Kluger V)	2005	FC/battery hybrid	Toyota in-house (90 kW)	High-pressure hydrogen (35 MPa)
Honda	FCX-V1 (EV Plus)	1999	FC/battery hybrid	Ballard Mark 700 (60 kW)	Hydrogen-absorbing metal alloys
	FCX-V2 (EV Plus)	1999	FC/battery hybrid	Honda in-house (60 kW)	Methanol reformation
	FCX-V3 (EV Plus)	2000	FC/ultra-capacitor hybrid	Ballard Mark 700 (62 kW)	High-pressure hydrogen (25 MPa)
	FCX-V4 (EV Plus)	2001	FC/ultra-capacitor hybrid	Ballard Mark 900 (78 kW)	High-pressure hydrogen (35 MPa)
	FCX (EV Plus)	2002	FC/ultra-capacitor hybrid	Ballard Mark 900 (78 kW)	High-pressure hydrogen (35 MPa)
	FCX (EV Plus)	2004	FC/ultra-capacitor hybrid	Honda in-house (86 kW)	High-pressure hydrogen (35 MPa)
	FCX concept	2006	FC/battery hybrid	Honda in-house (100 kW)	High-pressure hydrogen (35 MPa)
Nissan	R'nessa FCV (R'nessa)	1999	FC/battery hybrid	Ballard Mark 700 (10 kW)	Methanol reformation
	Xterra FCV (Xterra)	2001	FC/battery hybrid	Ballard Mark 900 (85 kW)	High-pressure hydrogen (25 MPa)

	X-trail FCV (X-trail)	2002	FC/battery hybrid	UTCFC (54 kW)	High-pressure hydrogen (35 MPa)
	X-trail FCV (X-trail)	2003	FC/battery hybrid	UTCFC (63 kW)	High-pressure hydrogen (35 MPa)
	X-trail FCV (X-trail)	2005	FC/battery hybrid	Nissan in-house (90 kW)	High-pressure hydrogen (70 MPa)
Mitsubishi	MFCV	1999	FC/battery hybrid	Ballard (40 kW)	Methanol reformation
	MFCV (Grandis)	2003	FC/battery hybrid	Ballard (68 kW)	High-pressure hydrogen (35 MPa)
Mazda	Demio FC (Demio)	1997	FC/ultra-capacitor hybrid	Mazda in-house (20 kW)	Hydrogen-absorbing metal alloys
	Premacy FCEV (Premacy)	2001	FC	Ballard Mark 900 (85 kW)	Methanol reformation

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*Source:* Nishimura (2007).

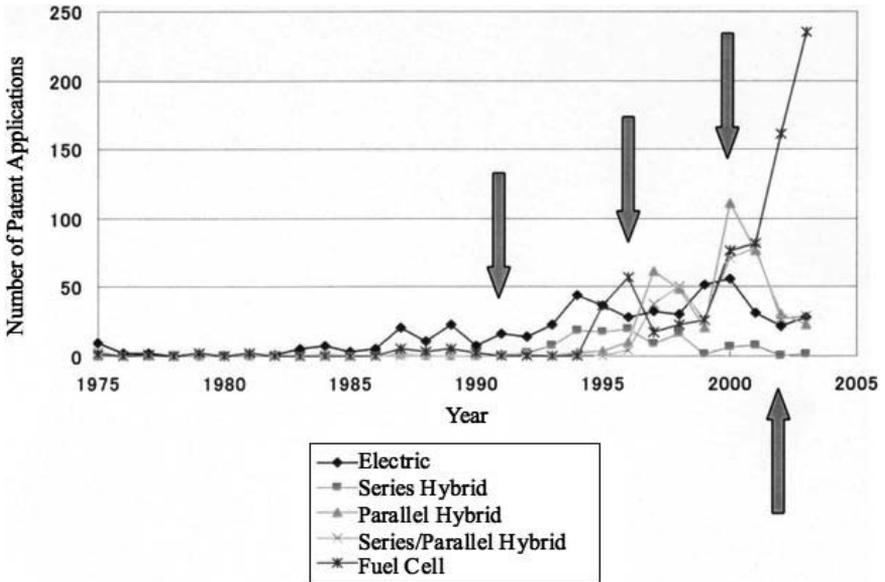


Figure 10.3 Patent applications by Toyota on clean vehicles

president, which was of decisive importance as an institutional framework in its strong leadership concerning environmental matters (*ibid.*). To support the activities of the committee, the Environment Affairs Division, comprising 50 staff members positioned just under the president, was created in 1998. The company's first Global Environmental Charter was released in 1992,<sup>3</sup> followed by an environmental implementation plan in 1993.

In September 1993 Toyota initiated a project, Global 21st Century (G21), to develop new automobile technologies for the next century. The original idea of the technical staff involved in the project was to pick up gasoline direct-injection technology, which would make it possible to improve fuel efficiency by 50 per cent. But the vice president in charge of the project at that time insisted on raising the target to a 100 per cent improvement in fuel efficiency. It quickly became clear that improving existing technologies would not be sufficient to achieve the target. This led to the rediscovery of the hybrid technology from among the technological options on which work had been undertaken earlier at the company's research centre. Originally, hybrid technology was developed in 1977 for a sports vehicle, the Toyota Sports 800 HV (Sasanouchi, 2003). Since then, research on hybrid technology had been conducted for

15 years at the research centre without receiving any particular attention regarding its commercial applications.

Then suddenly the development of hybrid vehicles was given top priority in Toyota's corporate strategy. The original target date for the commercialization of hybrid vehicles was set for December 1998. But the president pushed hard to put the new hybrid on the market at the time when the Third Conference of Parties to the UN Framework Convention on Climate Change (COP3 UNFCCC) would be held in Kyoto, Japan. This strong leadership contributed critically to introducing Toyota's first mass-produced hybrid vehicle, the Prius, to the Japanese market in December 1997, just after COP3 UNFCCC (Sasanouchi, 2000). The Prius was subsequently released in the US and European markets in 2000. Other hybrid vehicles, including the Estima and Crown hybrids, were commercialized in 2001. The trend in the annual sales of hybrid vehicles produced by Toyota is shown in figure 10.4. Recently the overseas sales of Toyota's hybrid vehicles, mainly in the United States, have surpassed those in the domestic market.

One of the crucial factors in Toyota's successful development of hybrid vehicles was the R&D strategy under which a diversified technological portfolio was maintained. Although the research on hybrid vehicles did

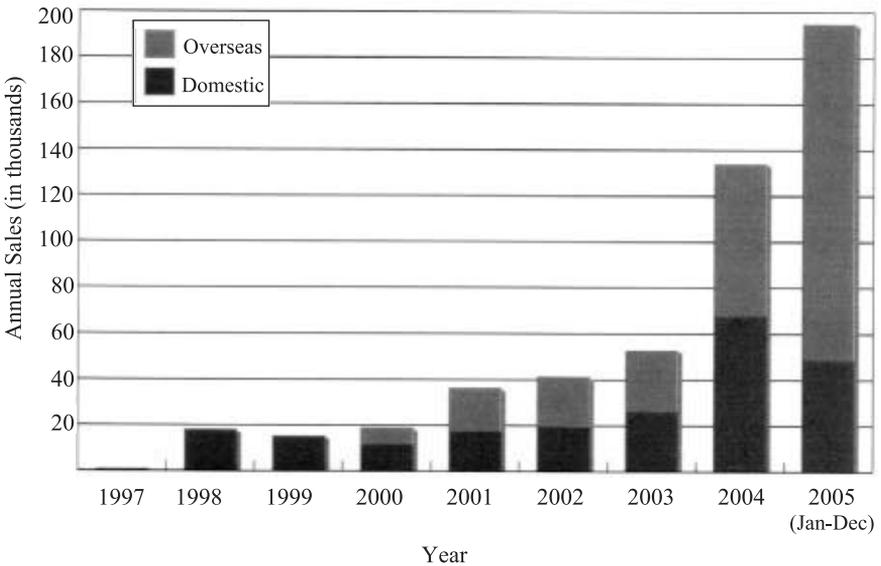


Figure 10.4 Annual sales of Toyota's hybrid vehicles

Source: Tanokura and Karishu, 2006.

not produce commercially significant results for a long time, the company did not abandon this technological option entirely. Because of this diversification of R&D, when the hybrid technology was later picked up for Toyota's G21 project, the company could quickly engage in developing hybrid vehicles. A closer examination of Toyota's patent applications on hybrid technologies reveals that its R&D preceded that of its rivals, Nissan and Honda, in almost all of the components and control techniques relevant to hybrid vehicles.

Hybrid vehicles are different from conventional gasoline vehicles in that the performance of the former relies crucially on batteries, motors and inverters, which are not contained in the latter (*The Economist*, 2004; Tachimoto, Hayashi and Kawabata, 2005). Thus it is of critical importance to have knowledge and experience of these new types of technologies in producing hybrid vehicles. And since fine-tuning between the engine and the motor is very important for increasing the fuel efficiency of hybrid cars, the development of electronic control systems was also essential.

Batteries, motors, inverters and control systems are indispensable components for electric vehicles in a broad sense, including fuel-cell vehicles as well as hybrids. In particular, battery technologies are the key to improving the performance of alternative clean vehicles. As Figure 10.5 shows, in the relationships that major auto makers have established with battery producers, close collaboration is vital to car makers in the development of electric vehicles in this broad sense.

In 1996 Toyota and Matsushita Battery Industry created a joint venture, Panasonic EV Energy, to provide nickel metal hydrate batteries for use in electric vehicles (Panasonic EV Energy, 2006). Their collaboration continued to develop nickel metal hydrate batteries, and later lithium ion batteries, for hybrid vehicles. Matsushita Battery Industry is, along with Sanyo Electric, one of the major battery producers in the world (Takeshita, 1999). Through its sustained experience of collaboration with Matsushita on electric and hybrid vehicles, Toyota obtained the necessary knowledge and expertise of these technologies and related problems and could later apply them in the development of fuel-cell vehicles.

Toyota's comprehensive development of fuel-cell vehicles, from materials, components and systems to control and production technologies, started in 1992 (Toyota Motor Corporation, 2004). In October 1996 the company demonstrated its in-house-developed fuel-cell vehicle, equipped with an original fuel-cell tank utilizing hydrogen-absorbing metal alloys. This vehicle was developed by modifying the electric vehicle Toyota had developed during almost the same period, the RAV4L-EV. In September 1997 the company unveiled the world's first fuel-cell vehicle with an

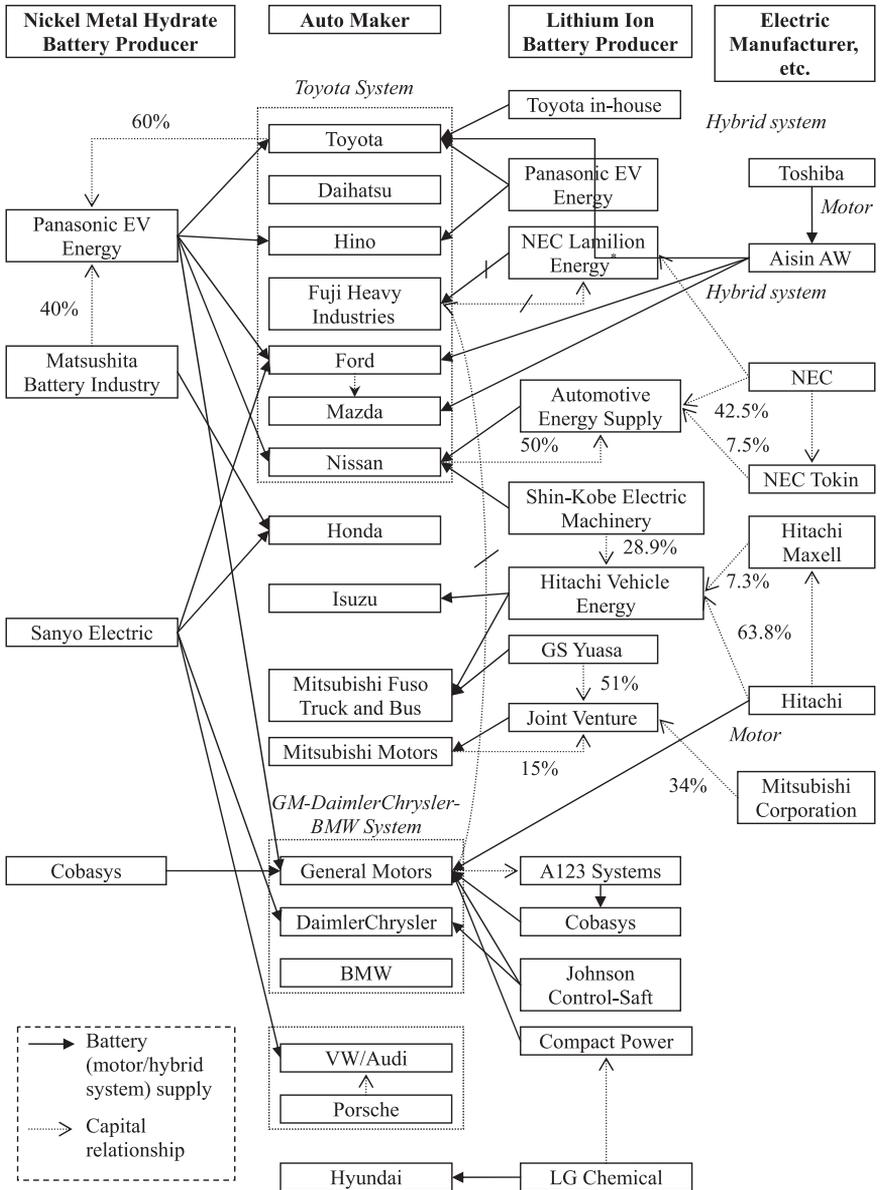


Figure 10.5 Relationships between auto makers and battery producers  
 Source: Center for Electric Vehicles (2006b), modified by the authors.

onboard methane reformer. In rivalry with the alliance between Daimler-Chrysler, Ballard and Ford with regard to the development of fuel-cell vehicles, Toyota started joint efforts with GM in 1999. In March 2001 Toyota announced the development of the FCHV-3, equipped with a fuel-cell stack featuring improved power output and a hydrogen-absorbing alloy tank, and in June 2001 the FCHV-4, equipped with high-pressure hydrogen tanks and the company's original fuel-cell stack. As the chronological development of fuel-cell vehicles by Toyota shows (table 10.2), from the beginning Toyota developed fuel-cell stacks in-house, rather than introducing technologies from outside companies, notably Ballard.

Testing of fuel-cell vehicles started on public roads in Japan and the United States. After Toyota's fuel-cell vehicles were certified by Japan's Ministry of Land, Infrastructure and Transport for the first time, the company began limited marketing with the delivery of two vehicles in the United States and four in Japan in December 2002. Recently, Toyota also announced that it would start road testing of plug-in hybrid vehicles in autumn 2007 (Takada, 2007). This strategic decision suggests that the company now takes plug-in hybrid electric vehicles seriously as a promising option for alternative clean vehicles.

### *Nissan and Honda: Reactive approach with technological selection and concentration*

The trends in patent applications by Nissan and Honda related to clean vehicles are given in figures 10.6 and 10.7, respectively. Technological development at Nissan and Honda progressed in accordance with the general trends in the Japanese auto industry, with a particular focus on their own fields of strength. A closer examination of patent applications shows that there are specific areas in which Nissan and Honda have developed technologies comparable to those of Toyota: Nissan has strength in the field of lithium ion batteries, and Honda in ultra capacitors. The trend in patent applications suggests, however, that the two companies conducted little R&D on series hybrid vehicles. Full-scale development of hybrid vehicles at these two companies was not conducted until the ZEV regulation was amended in 1996.

Figure 10.6 suggests that Nissan conducted R&D on electric vehicles at a level comparable to that of Toyota. Nissan's patent applications on electric vehicles were seen in the mid-1970s and continued during the 1980s. In the 1990s numbers increased sharply, and remained as many as 50 per year in the middle of the decade, followed by a rapid decline in the early 2000s. While Toyota initially worked on nickel metal hydrate batteries for use in electric vehicles, Nissan from the beginning focused

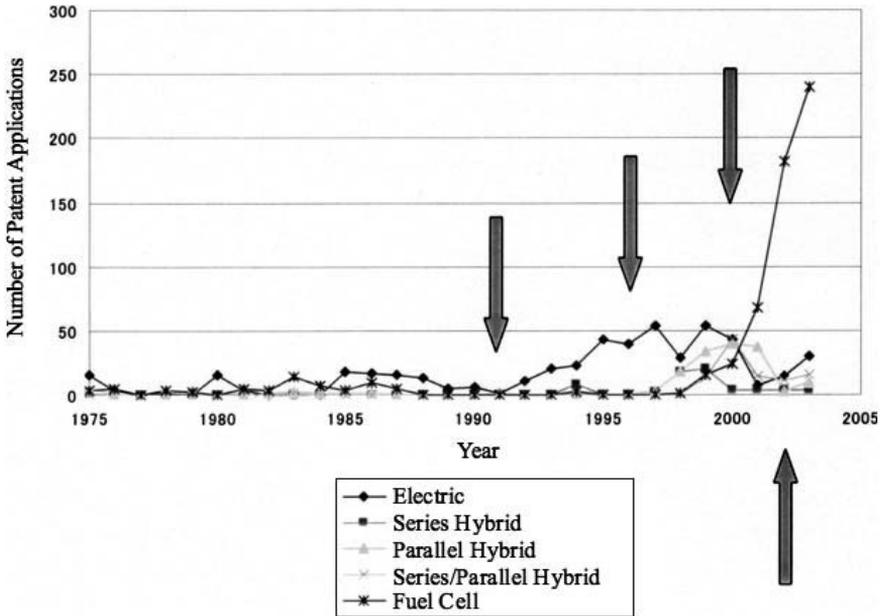


Figure 10.6 Patent applications by Nissan on clean vehicles

on lithium ion batteries, which were considered to be a more advanced technology. The company developed lithium ion batteries through collaboration with Sony, and released Tino hybrid vehicles in 2000. There remained many difficulties in the lithium ion battery system, however, which resulted in only limited development of Nissan’s electric vehicles by the end of the 1990s compared with those of Toyota or Honda (Sato, 1999). In terms of vehicle sales, while Toyota developed 10 different types of hybrid vehicles and had sold about 235,000 hybrids by 2005, and Honda approximately 48,000 hybrids by the same year, Nissan sold only 100 Tino hybrid vehicles based on the lithium ion battery system.

This initial experience of the development of lithium ion batteries might have discouraged Nissan’s subsequent R&D on hybrid vehicles. After its alliance with Renault in March 1999, the company virtually stopped the development of hybrid vehicles, giving priority to cost-cutting efforts (*Asahi Shimbun*, 2006). Instead, Nissan emphasized the importance of introducing ultra-low-emission vehicles based on internal-combustion engines, rather than hybrid vehicles, for improving air quality (Wada, 2003). Consequently, Nissan’s technological development lagged considerably behind that of Toyota in most of the technical fields related to hybrid vehicles. With the remarkable success of hybrids in the market,

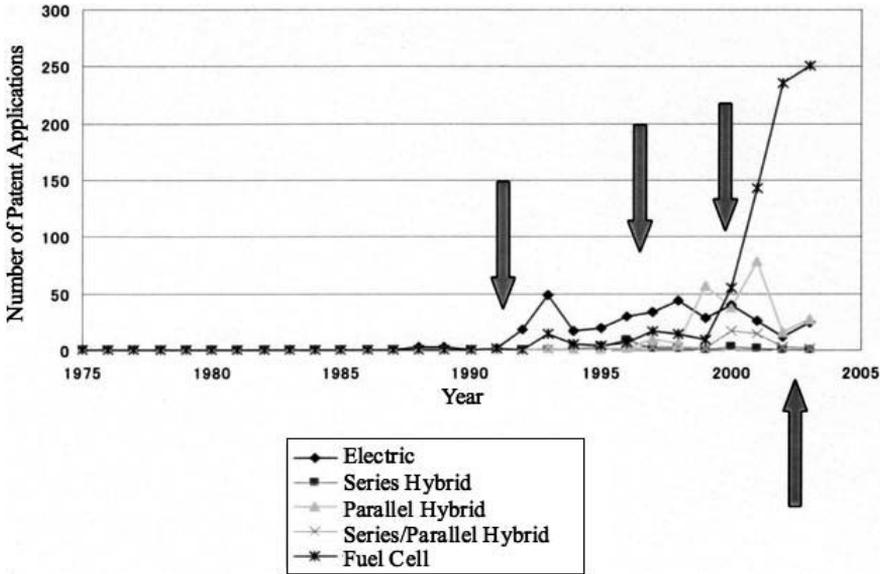


Figure 10.7 Patent applications by Honda on clean vehicles

however, Nissan announced in 2002 that it would make an alliance with Toyota to introduce hybrid technologies from its rival. Based on the supplied hybrid system, the Altima Hybrid was released in the North American market in February 2007. In its mid-term environmental action plan released recently, Nissan Green Program 2010 (NGP 2010), the company plans to develop hybrid vehicles with its original system to be launched in Japan and the United States, with a target of 2010 (Nissan Motor, 2006). Recently, Nissan established a joint venture with NEC and NEC Tokin for producing lithium ion batteries, Automotive Energy Supply (Karishu, 2007b). As lithium ion batteries are expected to be widely adopted in hybrid vehicles in the future, the company plans to sell its batteries to other auto manufacturers and primary suppliers.

Figure 10.7 suggests that Honda was not engaged in conducting R&D significantly until the late 1980s. In the early 1990s it started to develop nickel metal hydrate batteries jointly with Matsushita Battery Industry (Sato, 1999). Based on their successful development, Honda could introduce its first electric vehicle, the EV Plus, to market in California in 1997. Although figure 10.7 indicates that Honda did little R&D on hybrid vehicles until the mid-1990s, the previous experience of working on nickel metal hydrate batteries through collaboration with a leading battery producer could be considered to have helped the company develop hybrids

later. Honda succeeded in developing its own hybrid vehicles and began to sell the Insight in 1999. Its Civic hybrids were commercialized in 2001 and its Accord hybrids in 2004 in the North American market.

With regard to fuel-cell vehicles, figure 10.6 suggests that Nissan did a certain amount of R&D in the 1980s, but after that little was conducted until the mid-1990s. Nissan's patent applications on fuel-cell vehicles suddenly started to increase in the late 1990s, following Toyota's development of its first fuel-cell vehicle. In May 1999 Nissan announced that it had developed its first fuel-cell vehicle, the R'nessa, and started road trials (Homma, 1999). The vehicle was based on a methanol steam reformer developed jointly with the chemical engineering company Mitsubishi Kakoki Kaisha, the Ballard polymer-electrolyte fuel cell and a lithium ion battery. After concluding an alliance with Renault, Nissan decided in 2000 to invest ¥85 billion over five years for R&D on fuel-cell vehicles. In NGP 2010 the company plans to introduce next-generation fuel-cell vehicles into the United States and Japan in the early part of the next decade, with a key technology focusing on advanced fuel-stack systems.

In September 1999 Honda produced its first fuel-cell vehicle with a metal hydride battery, the FCX-V1, relying on the fuel-cell stack developed by Ballard (Moriya, 2003). One month later, at a motor show, the company exhibited its second fuel-cell vehicle, the FCX-V2, based on a methanol reformer and a fuel-cell stack developed in-house. In 2000 Honda announced the development of its third fuel-cell vehicle, the FCX-V3, equipped with a high-pressure hydrogen tank and Ballard's fuel-cell stack. Another version of the FCX-V3 was developed in 2001, with a fuel-cell stack developed by Honda this time. The company's fourth fuel-cell vehicle, the FCX-V4, was developed in the same year, equipped with a higher-pressure hydrogen tank and Ballard's fuel-cell stack. Subsequently, the company produced several types of fuel-cell vehicles with stacks developed in-house. In this way Honda adopted the fuel-cell stacks developed by Ballard at early stages and then gradually shifted to internal development.

### *Fuji Heavy Industries, Mazda and Mitsubishi Motors: Alliance and collaboration with foreign auto makers*

The clean-vehicle-related patent applications of Fuji Heavy Industries, Mazda and Mitsubishi Motors are shown in figures 10.8–10.10. Compared with their larger Japanese competitors, Toyota, Nissan and Honda, these three companies are relatively small, as indicated by the absolute amount of patent applications made for clean vehicles. It was hence difficult for them to devote a large amount of financial resources to research

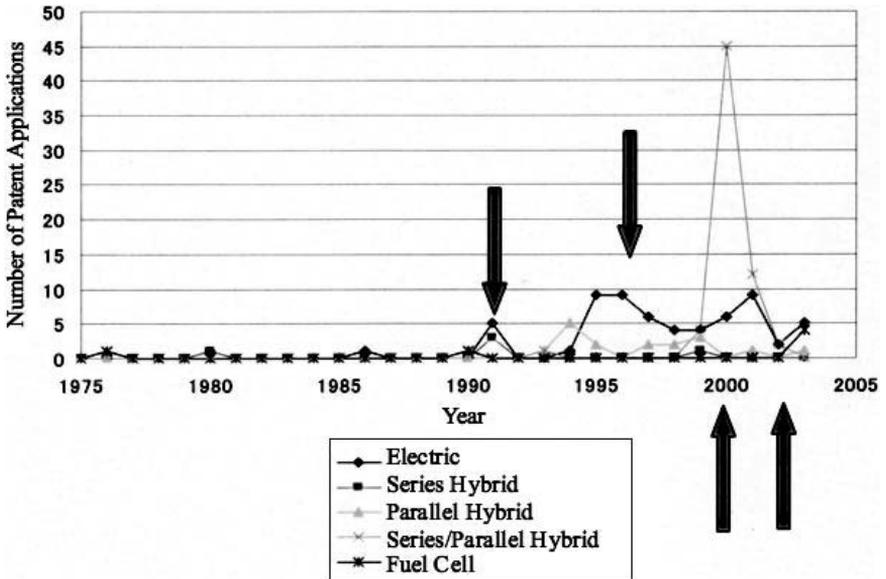


Figure 10.8 Patent applications by Fuji Heavy Industries on clean vehicles

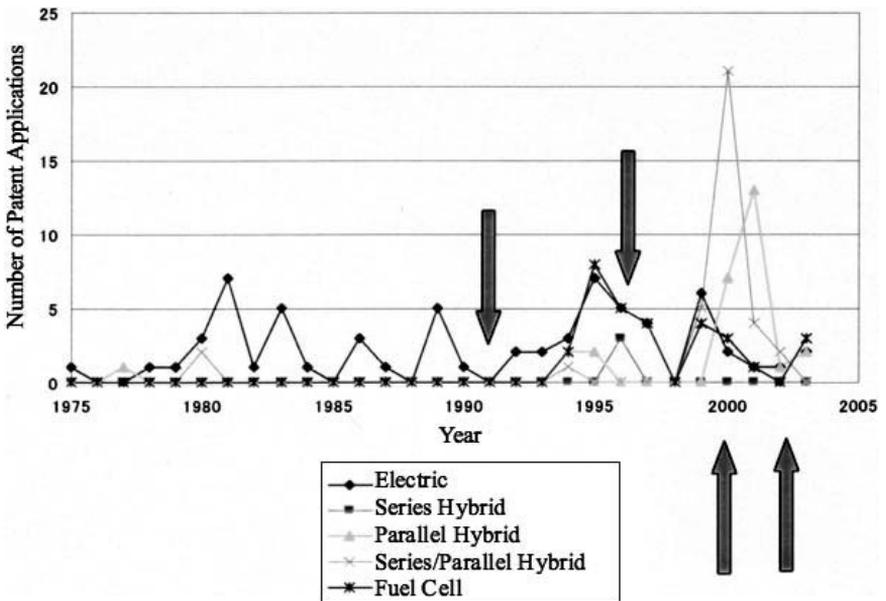


Figure 10.9 Patent applications by Mazda on clean vehicles

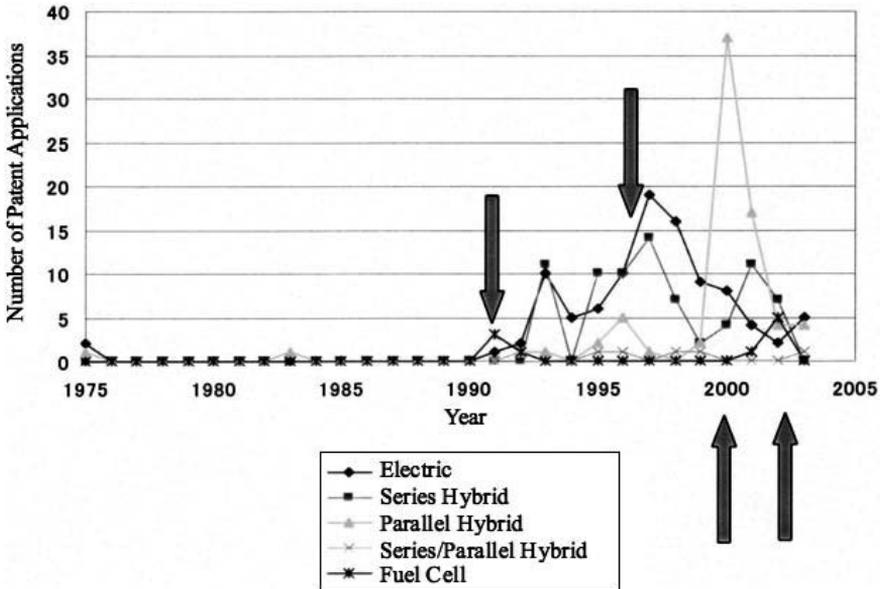


Figure 10.10 Patent applications by Mitsubishi Motors on clean vehicles

and development in new, advanced fields such as hybrid and fuel-cell vehicles.

From the mid-1990s to 2000 these companies formed or strengthened alliances with foreign companies. Fuji Heavy Industries started a capital and business tie-up with GM in 1999; Ford increased its holdings of Mazda shares significantly in 1996; and Mitsubishi Motors formed a capital and business alliance with DaimlerChrysler in 2000. Coupled with the revision of the ZEV regulation in 1999, these capital and technical alliances had a significant effect in encouraging these companies to conduct R&D on clean vehicles. The focus of patenting activity, however, was slightly different across the three companies. Fuji Heavy Industries patented mainly in series/parallel hybrid vehicles, Mazda in both parallel and series/parallel hybrid vehicles but with an emphasis on the latter, and Mitsubishi Motors in series hybrid vehicles initially and parallel hybrid vehicles later. Although Mitsubishi was able to develop its own technologies for hybrid vehicles relatively early, these were mainly for series hybrids and the company could not shift its R&D focus to parallel hybrids quickly. Fuji Heavy Industries established a joint venture with the major electric and electronic manufacturer NEC, NEC Lamilion Energy, for developing lithium ion batteries in 2002, and planned to develop hybrid vehicles with GM using the batteries (Karishu, 2007b). After Fuji

dissolved its capital relationship with GM in December 2005, however, the company withdrew from the joint venture in March 2006 and has started to develop hybrid vehicles through collaboration with Toyota. Mazda's hybrid vehicle, the Tribute Hybrid, and Ford's Escape Hybrid and Mercury Mariner Hybrid are based on the hybrid system developed by Aisin AW, a major component company which belongs to the Toyota group (Karishu and Tanokura, 2007).

On fuel-cell vehicles, Mazda actually revealed a trial model as early as in 1992, with a high-pressure hydrogen tank (Center for Electric Vehicles, 2006b). Following that, as figure 10.9 indicates, Mazda's applications for patents on fuel-cell technology increased, and in 1997 it developed its first fuel-cell vehicle, the Demio, with hydrogen-absorbing metal alloys. After Mazda made its alliance with Ford, the company joined the DaimlerChrysler-Ford project on fuel-cell development. Mitsubishi Motors gave up developing fuel-cell vehicles in 2006 and shifted its R&D to focus on electric vehicles (Nishimura, 2007). Recently the company developed its iMiEV electric vehicle for joint research with electric power companies, including Tokyo Electric Power Company, and aims at commercializing it in 2010 (Tomioka, 2006).

## Concluding remarks

This study argues that regulations combined with the particular strengths and weaknesses of individual companies have shaped the choice of technological direction and probably its speed, as reflected in R&D expenditures. The initial CARB regulations exercised a powerful influence on Toyota's R&D, since California was a key market for the company. Once the company had begun investing in electric and hybrid vehicle technologies, it chose to continue rather than abandon this pathway even though the regulations themselves were significantly weakened. Having worked on electric vehicles and nickel metal hydrate battery technologies, Toyota could accumulate experience and utilize it in revitalizing the development of hybrid vehicles maintained within the company. In this respect, by focusing on the advanced lithium ion battery too early, Nissan was not as successful in developing electric vehicles, which induced the company to abandon this technological option prematurely, including related hybrid vehicles. This suggests that there was a combination of vested interests, path dependence and regulatory impact affecting the principal market of sale at work here.

Somewhere along the line, however, Toyota also recognized that Daimler-Benz, later DaimlerChrysler, was a potentially huge threat, given

its rapid move along the learning curve in developing hybrid fuel-cell vehicles (HFCVs), as discussed by Ishitani and Baba in this volume. This probably stimulated the sharp upturn in research on HFCV technologies, which led to patent applications in the late 1990s in fuel-cell vehicle technologies. At the same time, as Mytelka argues in the introductory chapter of this book, once Toyota's hybrids began to take off thanks to US government subsidies to reduce the gap between the price of hybrids and internal-combustion engines, the rules of the game changed for every player, and all major car makers – such as Honda and Ford – had to produce hybrid vehicles, especially hybrid sport utility vehicles (SUVs). This buys time to develop further the technologies for HFCVs for the auto producers. It still remains to be seen when fuel-cell vehicles will actually be commercialized for the mass market.

In relation to developing countries, it should be emphasized that components, particularly batteries, will be crucial in developing electric vehicles in general, including hybrids as well as fuel-cell vehicles, and accordingly the relationship with suppliers will become much more important than in producing conventional gasoline vehicles. Distinct from conventional vehicles, hybrids depend on batteries, motors, inverters and control systems, and thus new types of knowledge on electric and electronic technologies are required in producing hybrid vehicles. While the proportion of electronic components in a vehicle is now approximately 20–30 per cent on a monetary basis, it is expected to increase to 50–60 per cent as electronic technologies are increasingly used for power-trains in hybrid vehicles (Okubo, 2006). Auto makers are now trying to develop “drive-by-wire” technologies, in which the mechanics of automobiles are entirely controlled electronically. Along with that, embedded software will become much more complicated in control systems, and this also requires close coordination with outside suppliers (Yarime and Baba, 2005). Under these circumstances, major auto makers in Japan and other countries have established close collaborations with leading battery makers and have accumulated experience of working on battery technologies. This is of considerable importance for the development of fuel-cell vehicles in the future. Therefore, the authors argue that it is desirable for developing countries to get into the production of hybrids as learning opportunities, although they might face more difficulties in entering this sector than in the case of producing conventional gasoline vehicles, as the level of required knowledge is higher and its scope more extensive. What is critically important is to find good suppliers of components and to establish a close collaboration with them for learning and accumulating knowledge on new sets of expertise. Rich experience of working on hybrid vehicles will also be valuable in producing plug-in

hybrids, which could prevail in the near future as they do not require the costly infrastructure of hydrogen, even if fuel-cell vehicles turn out to be the ultimate clean vehicles in the long run.

## Notes

1. In a series hybrid system, the engine runs a generator which can either charge the batteries or power an electric motor that drives the transmission. The engine never powers the vehicle directly. In a parallel hybrid system, the battery and engine are both connected to the transmission, and as a result either the battery via the electric motor or the engine directly to the transmission or a combination of both can provide propulsion power. The series/parallel system, combining both the series and the parallel systems, has a power diverter which can direct the energy from the engine to the wheels or to the generator. This means that, depending on the situation, the engine can provide propulsion to the wheels or energy to the battery (Rogoza Consulting Group, 2006).
2. See [www.jpo.go.jp/](http://www.jpo.go.jp/).
3. The Global Environmental Charter was revised in 2000.

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# 11

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## The race to develop fuel cells: Possible lessons of the Canadian experience for developing countries

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*Maureen Appel Molot*

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### Introduction

The auto industry, comprising vehicle assembly and parts production, is Canada's most significant manufacturing industry. In 2005 it accounted for 13 per cent of Canada's manufacturing gross domestic product, 20 per cent of its exports and approximately 20 per cent of new manufacturing capital expenditures, and it powers the economy of Ontario, Canada's largest province (Industry Canada, 2005). The industry is vibrant, with new investment in assembly and parts. The assembly sector is wholly foreign owned, which means that decisions on production – platforms and vehicles allocated to plants, production runs and plant closures – and on research and development (R&D) are made elsewhere (in the United States, Japan and Germany). Some auto industry R&D is done in Canada, but thus far not in leading-edge areas. In this regard, the Canadian auto industry resembles the industry in developing countries like Brazil, Mexico, South Africa, India and, to a lesser degree, China. With the exception of Mexico, these countries have all embarked on significant fuel-cell (FC) R&D programmes.

Canada is also host to a front-running fuel-cell sector in which firms like Ballard Power and Hydrogenics have been, and continue to be, key players. This chapter examines both sectors, and the extent of linkages between them. It begins with an analysis of the Canadian assembly and parts sectors and their place in an integrated North American auto industry. It then surveys auto industry R&D on new propulsion technologies.

The third section briefly describes the Canadian fuel-cell sector, and the fourth the extent of Canadian participation in the assembly and testing of alternative-propulsion vehicles. The chapter concludes with a discussion of the character of connections between the auto and fuel-cell sectors and lessons of the Canadian case for developing countries.

## The Canadian auto industry

### *Vehicle assembly*

Vehicle assembly in Canada is fully integrated with that in the United States and Mexico as the result of three agreements, two bilateral and one trilateral.<sup>1</sup> Ford, DaimlerChrysler (DCX),<sup>2</sup> General Motors (GM), Honda, Toyota and CAMI (a GM-Suzuki joint venture) all assemble vehicles in Canada. The first three original equipment manufacturers (OEMs) have a long history in Canada, while Honda, Toyota and CAMI opened assembly facilities in Canada in the mid- to late 1980s. All Canadian vehicle assembly takes place in Ontario, which overtook Michigan in 2004 as the largest vehicle-producing jurisdiction in North America.<sup>3</sup>

As mentioned above, the auto industry is Canada's largest and most important manufacturing industry. Approximately 85 per cent of assembled vehicles are exported (almost solely to the United States), as are two-thirds of Canadian-made parts.<sup>4</sup> Canada produces about 16.5 per cent of all vehicles assembled in North America, approximately twice the number bought by Canadians (DesRosiers, 2005a: 2). The industry accounts for 9 per cent of total manufacturing employment in Canada; one in six jobs in Ontario is linked to the industry.

Over the last decade the Canadian assembly sector has received between 18 and 20 per cent of annual Canada-US new capital expenditures in the sector; in 2003 Canada received 25.2 per cent of new assembly-sector dollars (DesRosiers, 2005b). In 2004–2005 Ford, GM, DCX and Toyota announced major investments in assembly capacity, either to upgrade existing facilities or to build a new assembly plant (Toyota).

With the integration of the Canadian and US assembly sectors following the Auto Pact, R&D and engineering expertise were centralized in the United States (Fitzgibbon et al., 2004: 21). The industry in Canada has traditionally focused on vehicle assembly and the maintenance of jobs that assembly generates directly and indirectly. R&D was not a priority.

In recent years the three traditional North American assemblers have begun to invest in R&D in Canada. GM made the most significant com-

mitment, investing in R&D and vehicle engineering activities at its Oshawa facility. Ford and Chrysler are also doing some R&D at their Canadian operations. But serious R&D capacity takes a long time to develop, so for the short and medium terms at least Canada remains on the R&D periphery. Canadian R&D tends to be an offshoot of that done at corporate headquarters. Although the governments of Canada and the province of British Columbia (BC) are supporting tests of Ford's hydrogen fuel-cell vehicles (HFCVs) in BC, Ford of Canada is not participating.<sup>5</sup>

The Canadian vehicle assembly sector is strong and is likely to remain so, despite the challenges currently being faced by the traditional Big Three OEMs. An important reason for this is the output by Honda, Toyota and CAMI, which in 2006 produced more than 900,000 vehicles (Roy and Kimanyi, 2007). Since the Canadian auto industry is integrated with that in the United States, a brief look at the overall North American market is an essential part of this analysis.

North America remains the world's largest vehicle market, but its auto industry, once dominated by the Big Three, is now facing aggressive competition from the "new North American assemblers" (NNAA), the Asian and European transplants. This competition is of three kinds: sales, profitability and R&D.

Ford, GM and DCX's market share for passenger cars has fallen steadily over the last decade, and their dominance of the light-truck market is also under attack as the NNAA increase truck production. Ford, DCX and GM had 73 per cent of market share in 1995 (DesRosiers, 2007b: 2); by June 2007 it was 50 per cent and by August it hovered at 48–49 per cent (Keenan, 2007a: B1). In 1990 the traditional Big Three OEMs produced 81.7 per cent of light vehicles assembled in North America; by 2006 this had fallen to 61 per cent (DesRosiers, 2007b: 2). All of the new vehicle assembly plants in the United States and Canada since 1990 have been built by the NNAA, with financial incentives offered by job-hungry US states (Molot, 2005) and since 2004 by the Canadian and Ontario governments. Toyota replaced GM as the largest seller of vehicles worldwide in the first quarter of 2007 (Maynard, 2007).<sup>6</sup>

There is considerable excess assembly capacity in North America. Assembly plants can produce 25 million vehicles annually, yet sales across the three countries are closer to 20 million (DesRosiers, 2007b: 1). The traditional Big Three have closed a number of assembly plants and will close more. Ford, GM and DCX are also struggling with serious financial situations. Stock values are uncertain and corporate bonds of GM and Ford now have "junk" status. All three, in contract negotiations with the United Autoworkers in late summer 2007, were trying to reduce their wage costs as well as their legacy obligations – the pension and health-care benefits of retired workers.

*Canadian parts sector*

The parts sector is an essential segment of the Canadian auto industry and, like assembly, is integrated into the North American vehicle production system. Two-thirds of vehicle components made in Canada are exported directly (almost solely to the United States) and many others are exported indirectly, in finished vehicles. Over the last decade capital expenditures in the parts sector have ranged between 7 and 12 per cent of North American investment in parts capacity; in 2005 preliminary estimates put the figure at 10.7 per cent (DesRosiers, 2005b). In May 2006 Honda announced the construction of a new engine plant in Ontario. Employment in the Canadian parts sector increased by about 40,000 jobs between 1992 and 2003, but by the end of 2006 had declined by 10,000 (DesRosiers, 2007c) to just over 92,000.

The Canadian parts sector depends heavily on sales to the traditional Big Three. Close to 85 per cent of components are sold to these OEMs. Some Canadian-owned parts firms sell to Toyota and Honda, but relatively few have cracked this market given the length of time these two OEMs have been in Canada and the number of vehicles they assemble.<sup>7</sup> Instead, a significant number of Japanese parts firms have followed their historic OEM customers to Canada.

The Canadian parts sector can be divided into three segments. The first (tier 1) is a group of globally competitive companies – Magna is now the second-largest parts producer globally – which account for about one-third of sector employment and output. The second and largest segment (tier 2) comprises subsidiaries of US parts firms, a small but growing number of subsidiaries of Japanese companies and a still smaller number owned by European parts firms; collectively this second group produces about half the sector's output and employs half its workers. The third group (tier 3), perhaps half of all parts firms, is made up of small Canadian companies that produce about 20 per cent of output and employ the same percentage of workers (Pilorusso, 2002).

There are a few other tier 1 companies in Canada besides Magna, but not many. The most important parts “sub-industries” in Canada are metal stamping, engines and parts (this segment is in flux with the impending closure of engine plants owned by the traditional OEMs and the opening of a new Honda facility) and plastic parts (Fitzgibbon et al., 2004: 17). There are a number of important parts categories in which Canada has little capability – electronics, drive-trains and steering suspension (DesRosiers, 2002: 4), batteries and regenerative braking (the latter two are important in hybrid vehicles).

Parts producers in the United States and Canada face continuing demands from the OEMs. Assemblers see cost reductions from parts sup-

pliers as one way to reduce vehicle costs. Assemblers want to limit the number of suppliers with whom they work and are encouraging (if not demanding) tier 1 firms to become system integrators (assembling components into vehicle segments). As a result the number of tier 1 suppliers has declined and a number of major suppliers that had previously shipped directly to the assemblers have become second-tier firms or left the industry (Fitzgibbon et al., 2004: 20).

Canadian parts producers are also facing competition from Asian and some Mexican suppliers. To meet the competition from Asia for lower-cost parts, as well as to supply the OEMs located in Asia, Magna has invested heavily in that region;<sup>8</sup> other Canadian firms are considering Asian investments, though the small size of many Canadian parts producers makes this difficult (Beauchesne, 2006).

Because of their dependence on the traditional Big Three and the continuing demands for price reductions, most Canadian parts firms have tight profit margins and short time horizons. Their ability to remain solvent depends on fulfilling current sourcing agreements, anticipating the next opportunity to bid and hoping they can meet the competition. The declining market share of the traditional Big Three and the rise in value of the Canadian dollar since 2003 are adding to the challenges facing Canadian parts firms.

Canadian parts producers do some R&D, but it tends to be focused on activities with an immediate pay-off. Most R&D is on process technologies that will help meet assembler demands on price, delivery times or engineering and design. Since many of the larger firms in the sector are subsidiaries of MNEs, much of their R&D, and any that is leading edge, is done elsewhere (Fitzgibbon et al., 2004: 22). The major exception to the relatively short-term focus of parts-firm R&D is Magna, which because of its size and diversity of activities can afford to invest in R&D with a longer-term pay-off.<sup>9</sup> And Dana Corporation's Canadian subsidiary is doing some work on heat-exchanger products and hydrogen fuel-processing systems for its parent, which has contracts with GM, for example to produce components for hybrid vehicles. But overall, with a few exceptions, Canadian parts suppliers are not involved in R&D around alternative fuels.

## Auto industry R&D on alternative fuels

### *Fuel-cell vehicles*

Inter-firm R&D competition is intense. The major competition is over fuel-cell technology and, increasingly, around hybrids and electric vehicles.

The assembler that is the first to produce a reliable and reasonably priced FC vehicle will enjoy a significant first-mover advantage. Most OEM leading-edge research is done in-house or close to head offices, though some are now conducting research at their foreign locations.<sup>10</sup> DCX's fuel-cell R&D is based in Germany, that of Ford and GM in the United States and Toyota, Honda and Nissan in Japan. The same is true for research on hybrid and electric cars.

Rising energy costs, fears about security of supply and concerns about global warming and the environment are all pushing the OEMs to expend large sums on work on alternative-propulsion vehicles. In the two-year interval between the conference that generated the chapters for this book and authors' revisions, the R&D effort has intensified as OEMs compete with each other on environmentally friendly vehicles. At the 2007 Detroit, Los Angeles and Frankfurt auto shows, all high-profile opportunities for OEMs to demonstrate their latest technologies, most assemblers devoted considerable attention to new-generation vehicles, including FCVs, hydrogen-fuelled internal-combustion engines (ICEs) and electric- and diesel-powered products (DesRosiers, 2007a; Crawley, 2007: 2). At the April 2007 Shanghai Motor Show two of China's biggest OEMs showed experimental FC vehicles (*Fuel Cell Today*, 2007a). A 2007 *Fuel Cell Today* report on HFCVs stated that "many of the key automotive manufacturing companies have announced plans for fuel cell concept vehicles and some have even gone as far as proposing dates for commercialization much earlier than had been previously anticipated" (Crawley, 2007: 1). To cite but a few examples, Honda expects to launch FC vehicles on the global market by the end of the current decade, GM anticipates production of its FC-powered Chevrolet Sequel by 2010, BMW expects to roll out a hydrogen-fuelled ICE by 2008, Ford is working on its HySeries Drive vehicles and Toyota continues work on its FC cars, noting that it has reduced the time required for sub-zero start-up for such cars. Crawley (*ibid.*: 4–5) also notes that in 2006 North America was the dominant region in which FC vehicles were being developed, in contrast to 2005 when development was spread fairly evenly across Asia (excluding Japan), Japan, Europe and North America.

The range of HFCVs being built is increasing, as is the number of vehicle tests.<sup>11</sup> DCX is testing five HFC cars at Los Angeles airport and has three test vehicles with a California power company (*ibid.*: 14); it has also been testing 100 HFCVs in various locations (*Globe and Mail*, 2005). Moreover, the company has been a major producer of fuel-cell buses, which have been on trial in a number of major European cities. With its own resources as well as support from the US Department of Energy, GM is deploying FC demonstration vehicles in Washington, New York, California and Michigan. Shell Hydrogen is supporting GM by setting

up five hydrogen refuelling stations in Washington and New York, between these two cities and in California (*National Post*, 2005). GM also demonstrated one of its FC vehicles at the 2007 FC Expo in Japan (Crawley, 2007: 9). Ford's distribution of HFCVs for trials in US and Canadian cities is evidence of that firm's FC R&D. In May 2007 Ford initiated a trial of eight hydrogen-fuelled buses in Orlando, Florida (*Fuel Cell Today*, 2007b). Japan has a demonstration programme with 60 vehicles and 10 refuelling stations, and has plans to commercialize 5 million fuel-cell vehicles by 2020. In sum, most of the OEMs are involved in some R&D on, and testing of, FC vehicles in their home economies and sometimes in other locations.

A critical issue in this R&D, with implications for the Canadian auto industry, is the identity of the FC stack suppliers with which the assemblers are working. Ballard Power Systems of Vancouver, the unquestioned leader with respect to proton-exchange-membrane (PEM) fuel cells (the technology in widest use – Crawley, 2007: 3), supplies the technology to six of the assemblers. It is providing more than half the FCs used in the tests of HFCVs in different locations in the United States and Canada (*Globe and Mail*, 2005). In addition to Ford and DCX, Ballard has supplied fuel cells to GM, Honda and Nissan (Bourgeois and Mima, 2003: 91). Hydrogenics of Toronto has an alliance with GM to assist in the production of its in-house FC system (Avadikyan and Larrue, 2003: 134). Beyond Ballard and Hydrogenics, few Canadian firms fall into the most-trusted-supplier category – those firms with which the traditional Big Three are engaged in the critical R&D around HFCVs (*ibid.*: 146–149). The connection between Canadian firms active in the fuel-cell sector, whether the FCs themselves or the hydrogen infrastructure, and the vehicle assemblers is generally mediated through OEM head offices.<sup>12</sup>

### *Hybrid vehicles*

The pressures underlying the race to develop FC vehicles are also pushing the auto industry to focus on short- and medium-term innovations. The intermediate technology, which most assemblers are now developing to diffuse across existing models, is the hybrid, a car that uses both an ICE and a battery for propulsion. From a vehicle that aroused mild interest when it was first demonstrated some years ago and which was not seen as a significant innovation, hybrids are now the subject of intense competition among assemblers. Toyota, which sold its first hybrid vehicle in 1997, is now producing a third-generation Prius and anticipates that all its vehicles will have a hybrid model in the relatively near future. By 2010 Toyota anticipates selling 1 million hybrid vehicles annually (Katz and

Inoue, 2005), including 600,000 in the United States (Brooke, 2005). At the end of May 2007 Toyota announced that it had sold more than 1 million hybrid vehicles worldwide (*National Post*, 2007). Ford, which currently makes its Escape SUV as a hybrid, wants to position itself as a major player in the hybrid vehicle market (*Ottawa Citizen*, 2005).<sup>13</sup> In September 2007 Chrysler announced the creation of a new unit to “jump-start” its development of hybrid and electric vehicles, both market segments in which the company now lags (Krolicki, 2007).

In the competition around hybrid vehicles, Toyota is the leader and aims to make its technology the industry standard (Rechtin, 2005). Toyota holds far more hybrid patents than its competitors. In fact, some of the other OEMs producing hybrids – Ford and Honda – have been licensing Toyota technology in addition to working to develop their own. The number of Toyota patents on hybrids has generated what one senior auto parts executive termed a “patent minefield”, expensive to review and move beyond.

Toyota’s success with hybrid technology has thus had an impact on the R&D priorities of its competitors.<sup>14</sup> And at this juncture in the global auto industry, Toyota has far deeper pockets than other OEMs. It will be some years before Ford makes a profit on its hybrid Escape and, with the exception of Honda, the other assemblers are playing catch-up. Anticipating its first hybrids in late 2007, GM would appear to have misjudged the trajectory of new automotive technologies. The company, which at one point derided hybrids, recognized in 2005 that it had no option but to develop them. A BMW executive explained his company’s decision to participate in the development of hybrids in language that captures the challenges all assemblers face as a result of the first-mover advantage Toyota, and to a lesser degree Honda, has in hybrids: “The creation of a shared technology platform for hybrid drives will allow us to more quickly integrate the best technologies on the market and will therefore exploit and strengthen the innovative potential of all participating companies” (Shields, 2005). In other words, assemblers and their suppliers are not going to move from ICEs to HFCVs in one step. Interim steps are required, of which the hybrid is a significant one, largely for the learning involved.

Most of the critical parts for hybrid vehicles are sourced in Japan. Although Toyota imports some, if not most, of the significant hybrid components – the battery, electronics and power-train – for the hybrids it assembles in North America, it will have to develop North American supply capacity. This is one of the reasons why the Asian OEMs are now investing heavily in R&D centres in the United States. Although R&D on power-trains, electronics and vehicle architecture is, and will likely continue to be, done in Japan, the North American centres will be

responsible for sourcing parts from North American suppliers and working with these suppliers to create components and adapt technology developed abroad for vehicles assembled and sold in North America (Truett, 2005: 1, 49).

## Canada's fuel-cell sector

Canadian companies were early movers in research on, and commercialization of, capacity in fuel cells and related technologies. Ballard Power Systems is a world leader in PEM fuel cells and has strategic alliances around the world, including as noted above with many of the OEMs. Although Canada ranks fifth in the number of fuel-cell patents by country (Liston-Heyes and Pilkington, 2004), the Canadian fuel-cell industry ranks highly when measured in terms of the number of firms in the sector and the range of technologies covered. There are two major fuel-cell clusters in Canada, the larger one in the Vancouver, BC, area around Ballard Power Systems, and the second in the Toronto area around Hydrogen Village.<sup>15</sup> There are also firms producing inputs for the hydrogen economy or doing fuel-cell R&D in Alberta and Quebec.

Canadian companies are working in a number of areas relevant to the hydrogen economy: infrastructure, including H<sub>2</sub> production, delivery and storage; mobile applications, such as buses, cars and industrial vehicles; stationary applications, including back-up power and residential heating; and portable power (Government of Canada, 2005: 4). Beyond Ballard and Hydrogenics, other Canadian FC firms have connections with the assemblers – Dynetek Industries with Ford, DCX and Nissan, and Praxair with Mercedes. In addition to the longstanding Ford and DCX investment in Ballard Power Systems, other OEMs have provided Canadian FC firms with capital. Many Canadian FC companies have international connections. Firms in this sector have research, marketing, demonstration and financial relationships with companies in the United States, Europe and Asia. For example, as a result of its acquisition of Stuart Energy, Hydrogenics has ties in Europe and Asia. It has a subsidiary in Europe that produces hydrogen using electrolysis; it also works with companies in Europe and elsewhere on issues related to the generation and storage of H<sub>2</sub>.

Alliances and partnerships are important for the Canadian FC sector. Their number increased from 135 in 2002 to 256 in 2003: the largest number of alliances were with vehicle assemblers (33 per cent); those with other hydrogen and FC developers and public-private partnerships ranked second (at 20 per cent each) (Government of Canada, Fuel Cells Canada and PriceWaterhouseCoopers, 2004: 7). Figure 14.3

in Fitzgibbons's chapter in this volume illustrates the regions in which Canadian FC firms are involved in demonstration projects.

Although the Canadian FC sector is active in R&D, firms in the sector are financially precarious. Many are small, dependent on government support and have difficulty raising the venture capital required for R&D and commercialization. Chapter 14 in this book identifies a range of financial issues facing the sector.

Fitzgibbons's chapter also details the breadth of federal Canadian government support for fuel-cell R&D and commercialization. This support involves several government departments and the National Research Council (the government's primary institution for R&D in the fields of science and engineering), as well as some important funding programmes which provide support for high-risk, pre-commercialization research. Although the Canadian government has been a proponent of FC technology and has created programmes to underwrite some R&D costs, it does not appear to appreciate, or be able to provide, the level of resources required to sustain a serious Canadian presence in the costly and competitive race to develop and commercialize alternative fuels. As Fitzgibbons notes in his conclusion, the government's 2005 discussion paper on a national hydrogen and FC strategy (Government of Canada, 2005) has not moved forward. Nor is the government promoting linkages between the FC and automotive sectors, although through the Canada EcoTrust for Clean Air and Climate Change the federal government is contributing to British Columbia Transit's purchase of 20 fuel-cell buses and the province's development of fuelling stations, which will constitute the centrepiece of BC's Hydrogen Highway project (Crawley, 2007: 11).

As Fitzgibbons outlines in chapter 14, Canadian provincial governments also have programmes to promote H<sub>2</sub> technologies, but neither of the two provinces with the major FC clusters is investing heavily in the technology. BC's goal is to have the world's leading hydrogen economy by 2020: its H<sub>2</sub> strategy is shaped by the presence of Canada's largest fuel-cell cluster, the Hydrogen Highway, which is a large-scale demonstration project for HFCVs, refuelling stations and stationary power systems to be developed for the 2010 Winter Olympic and Paralympic Games, and the revitalization of the province's resource heartlands to supply the fuel and know-how for hydrogen-based communities and industries (Premier's Technology Council, 2004: ii). But although BC has provided C\$33 million in funding to the FC sector over the years, the province's fiscal constraints impose limits on capacity to underwrite its hydrogen strategy statement.

The Ontario government announced its Fuel Cell Innovation programme in January 2005. The programme provides C\$3 million in annual funding over three years, with a focus on product commercialization. The

funds are designed to nurture the development of small and medium-sized Ontario companies working on FC technology development and FC-compatible strategies ([www.fuelcells.2ontario.com](http://www.fuelcells.2ontario.com)). Given the cost of FC R&D and the range of challenges to commercialization, this government support is small and suggests that FCs and the hydrogen economy are not a priority. Moreover, despite the importance of the auto industry to the Ontario economy and the provincial Liberal government's introduction of a programme to attract OEM investment in new and upgraded plants, the government has not promoted or facilitated connections between the auto and fuel-cell sectors. The Ontario H<sub>2</sub> programme focuses more on stationary and portable power applications of fuel cells than on mobile uses. In June 2007 the Ontario government announced a C\$650 million fund aimed at stimulating the development of green technologies, including in the auto industry. It is too early to identify any real impact of this new fund, although one executive of a Canadian OEM subsidiary commented that the availability of these resources "will make it easier to make a business case for green-technology investments in Ontario" (Lindgren, 2007).

## Linkages between the Canadian auto and FC sectors

The connections between the auto and FC sectors fall into two categories: manufacturing, and testing and demonstration projects. While the following discussion demonstrates that there are a number of initiatives in Canada that are important in terms of learning for the future (beyond vehicle assembly), as noted above decisions with respect to manufacturing are made outside Canada. Just as critical, the linkages between the FC firms and vehicle and forklift assemblers largely go through firm headquarters, again outside Canada. The exception is the FC bus project in Vancouver; New Flyer, the Winnipeg-based company that will produce the vehicles, has contracted with Ballard to supply the fuel-cell modules for these buses (Ballard Power Systems, 2007).

Beyond the FC bus assembly, there is one FC vehicle assembly project in Canada: in September 2006 GM announced that it would build 100 HFC Equinox SUVs in Canada. Production of this vehicle will be done in two stages at two different plants. The basic assembly of the Equinox, the first and thus far only FC vehicle engineered and manufactured in Canada, will be done at CAMI (the GM-Suzuki joint venture in Ingersoll, Ontario); final assembly, including the engines and FC stacks, will be done at GM's regional engineering centre in Oshawa (Malloy, 2006). In addition, there have been two commitments to build hybrid vehicles in Canada. In early 2006 Ford announced that it would produce hybrid

versions of two of its vehicles at its Canadian assembly plant by 2010 (Keenan, 2006). In February 2007 GM indicated that it would build hybrid variants of two of its pick-up trucks for sale in 2008 (Van Praet, 2007a). As noted above, parts producers in Canada are doing little R&D related to alternative technologies and firms in Canada are not directly supplying any of the components needed to transform internal-combustion engine vehicles into FC or hybrid ones.

There is considerably more activity in Canada with respect to demonstration projects and testing of FC and hybrid vehicles. The first FC bus demonstration, using a Ballard FC stack, took place in Vancouver in 1993. Since 2005 six hybrid buses have been part of the fleet of a mid-size BC city.<sup>16</sup> The most significant bus demonstration project will be the 20 FC buses that will ply BC's Hydrogen Highway for the 2010 Winter Olympics. BC has also been the site for a major test by Ford of its five Focus FC cars, which are powered by Ballard FC stacks.<sup>17</sup> Three mostly made-in-Canada Ford hydrogen fuel-cell shuttle buses started a test run on Parliament Hill in Ottawa at the end of 2006. Hydrogenics has supplied the FCs to Purolator for that firm's hydrogen fuel-cell hybrid electric vehicle (PriceWaterhouseCoopers, 2006: 7). Finally, Powertech Labs (PTL), a subsidiary of BC Hydro, is testing vehicles for a number of OEMs, including Toyota, Ford, DCX, GM Hyundai and Nissan (the latter two of which do not assemble vehicles in Canada). PTL has developed a worldwide reputation for its expertise, and most of its business comes from outside Canada.<sup>18</sup>

## Conclusion

This chapter analyses the characteristics of the Canadian auto and fuel-cell sectors to derive lessons from the Canadian experience for developing countries. Without question the Canadian auto industry is robust, with new investments in assembly and parts and strong employment figures despite some plant closures. But neither segment of the industry is actively participating in the race to develop and commercialize FC and hybrid vehicles. OEMs hold leading-edge research close, and very little critical research is done at subsidiaries. OEM decisions have meant that their Canadian plants emphasize vehicle production and conduct only narrowly focused R&D. The exception is GM, which has just designed its first vehicle in Canada. Canadian parts firms of necessity have short time horizons and, to the extent that they undertake R&D, do it on process rather than leading-edge technologies. There is some testing being undertaken in Canada, with the potential for more. The situation of the Canadian auto industry is not unusual for a small, open economy in

which critical decisions on vehicle assembly as well as R&D are made outside the country.

Domestic linkages are developing between the auto and fuel-cell sectors, but these are largely mediated through OEM head offices. There seems to be little governmental attention to this situation and its consequences. Canadian governments at both levels are supporting FC R&D, although whether they are doing so sufficiently relative to the costs of R&D, timeframes to commercialization and funding levels in other countries is another matter. The new Ontario green technology fund may spark some R&D, but it is too early to be able to indicate anything other than the presence of this initiative.

Lessons can be drawn from the Canadian experience for developing countries engaging in R&D in the fuel-cell sector. Perhaps the most fundamental is the importance of building a strong domestic knowledge base in both auto and FC sectors. R&D capacity in assembly and parts, including attention to leading-edge technologies, is essential to participating in the development of the new vehicle-propulsion systems. As the Canadian case shows, despite its attractiveness as a site for vehicle production, the essentially assembly character of the Canadian auto industry raises doubt about its ability to play a significant role in the R&D around, and commercialization of, HFCVs. In part this is because deep corporate and government pockets and commitment are necessary as a result of the cost of leading-edge research and the challenges of its commercialization. But it is also a result of the absence of an indigenous auto industry and the limited ability of Canada's parts firms, thus far, to become first-tier preferred partners of the OEMs in the development of parts at the core of the new propulsion technology. Whether this is possible at all, and through what means, remains to be seen.

With the exception of China, developing countries with automobile assembly industries are not likely to become major players in the development and application of H<sub>2</sub> technology in the near future. However, learning and capacity building in their parts sectors could take place through licences to produce relevant parts should global OEMs decide to build hybrids or HFCVs in countries like Malaysia, India, Brazil or South Africa. Attention will need to be paid to building alliances with these firms to encourage such activities. Policies will need to be put in place not only to strengthen domestic research capacity but also to open opportunities for linkages to users. Governments should pay particular attention to orienting R&D and demonstration projects to meet local needs – such as in stationary power and niche markets in the transport sector, including two- and three-wheeler vehicles and fleets like hybrid taxis, where local firms might emerge as assemblers, component manufacturers and systems integrators. In some cases, such as India and

Malaysia, the development of hydrogen FC two- and three-wheel vehicles is already under way and should be further developed and diffused. In countries with sufficient land and technological capabilities the development of new fuels such as ethanol, biodiesel and hydrogen would provide yet another entry point for participation in the emerging hydrogen economy.

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## Notes

1. The first was the Canada-US Auto Pact signed in late 1964, which promoted rationalization of vehicle assembly between Canada and the United States. It was followed by the Canada-US Free Trade Agreement, implemented on 1 January 1989, and the North American Free Trade Agreement, which took effect on 1 January 1994. Vehicles and parts move tariff-free across borders as long as content requirements (62.5 per cent under NAFTA) are met. Each NAFTA member retains its own tariffs on vehicles and parts imported from non-NAFTA members.
2. In the spring of 2007 Cerebus Capital Management bought 80 per cent of Chrysler from Daimler-Benz, thus ending the nine-year merger between the German and US vehicle assemblers. Since the break-up of DCX occurred after the timeline covered by this analysis, the company will be referred to as DCX, with the exception of a reference in the section on hybrid vehicles.
3. In 2004 assembly in Ontario surpassed that of Michigan by about 100,000 vehicles. By 2008 the difference is projected to be more than 500,000 (Durbin, 2005a). Ontario will suffer less than Michigan from the decline in traditional Big Three assembly because of the assembly capacity of Honda and Toyota in Ontario. In contrast, none of the new US assembly capacity built by the new North American assemblers is in Michigan.
4. Ninety per cent of the vehicles purchased in Canada are imported, 65–70 per cent from the United States, the remainder from offshore. Seventy to 75 per cent of parts used in vehicle assembly in Canada are imported.
5. The data on vehicle operations are sent directly to Ford's research division in Michigan (interview with official from Hydrogen and Fuel Cells Canada).
6. In mid-2007 vehicle sales in the United States were declining as a result of falling consumer confidence in light of the weakness in the US housing market and the credit crunch, but sales in Canada remained strong (Van Praet, 2007b). Because so much of Canadian vehicle output is exported, declining US sales have a direct impact on Canada. In late August 2007 GM announced it would cut 1,200 jobs (one shift) at its pick-up truck plant in Oshawa, Ontario.

7. A survey of North American parts suppliers suggests declining confidence in the traditional OEMs and a preference for working with the Japanese assemblers. Parts makers indicated their intention to raise R&D budgets and capital expenditures for Toyota, Honda and Nissan while reducing them for the Big Three (Durbin, 2005b). These reports do not indicate whether Canadian parts producers were included in the survey. However, the survey results fit with interview comments about the difficult relationships between Canadian suppliers and the traditional North American OEMs.
8. In September 2007 Magna had 25 plants in Asia, and it expects the number to increase to 30 in the next couple of years. In addition to manufacturing plants, Magna has engineering and product development facilities in China (four of them), Japan and South Korea (Keenan, 2007c).
9. An August 2007 article reporting on Magna's very profitable second quarter of 2007 suggested that, recognizing OEM interest in hybrids, the company "is considering a major new strategic initiative that will involve developing components for hybrid engines" (Keenan, 2007b).
10. *Fuel Cell Today* (Crawley, 2007: 16) reports that GM has announced plans to open an R&D office in Moscow which will focus on hydrogen and fuel cells, among other projects.
11. *Fuel Cell Today* forecast that by the end of 2007 there would be over 250 new HFCVs built, for a total of close to 900. The total number of HFCVs in 2005 was about 300 (Crawley, 2007: 2).
12. Though not in the automotive sector, Canadian or Canadian-based FC firms have also been producing FCs for forklift vehicles and participating in tests of these vehicles. In June 2007 Hydrogenics released the latest generation of its HyPX Power Packs after successful tests in 2005 of its previous Power Packs in two forklift trucks at GM's Oshawa plant and the FedEx facility at Toronto airport (*Fuel Cell Today*, 2007c). Cellex and General Hydrogen, both located in the Vancouver area and both purchased in 2007 by Plug Power, are involved with a number of US retailers in tests of pallet trucks. Both companies use Ballard FC stacks (Adamson, 2007).
13. Ford has plans to assemble hybrid versions of the new Ford Edge and Lincoln MKS cross-over utility vehicles at its upgraded Oakville, Ontario plant, though no production date has been announced. Ford expects to sell 250,000 hybrids annually by 2010 (Keenan, 2006).
14. The competition among OEMs around hybrid technology extends to China. GM and Shanghai Automotive Industry Corporation have agreed to explore ways to expand a hybrid bus development programme. GM and SAIC will also work on hybrid cars as well as HFCVs (Webb, 2005). Toyota now produces its Prius in China.
15. Hydrogen Village works with companies in southern Ontario to promote R&D and demonstration projects to develop and promote the hydrogen economy.
16. The buses are made by New Flyer; GM supplied the hybrid system.
17. The programme runs for five years and is supported by the governments of Canada and British Columbia, Hydrogen and Fuel Cells Canada and Ford.
18. PTL has more US corporate clients than from any other country. Japanese companies rank second, those from Germany third and those from Canada fourth.

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## 12

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# Automobile emissions and the environment: The Malaysian experience

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*Fatimah Kari and Rajah Rasiah*

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### Introduction

Since the turn of the new millennium, the automobile industry has been in the grips of three major changes: increased liberalization that has seriously reduced the opportunity for further latecomer national car development policies; rationalization that has reduced production platforms to specialized locations; and the proliferation of environment-friendly technologies in the industry. With the exception of developing economies with huge domestic populations, such as China and India, national automobile assembly has either declined in importance or the shakeout from competition has reduced the manufacture of components to a few locations (e.g. Brazil, South Africa and Taiwan) that offer cutting-edge technologies and the agility to respond quickly to changes in demand on a global scale. The rising demand for cleaner technology, especially in the major markets of Europe and the United States, has moreover attracted increasing investment in environment-friendly vehicles and fuels. In addition to outright bans, legislation in Europe and the United States has stimulated the demand side for environment-friendly products through taxation on the use of polluting and non-renewable resources.

This chapter explores the consequences of these developments for automobile development and related environment and energy policies in Malaysia. Given the focus on institutions and systemic influences, the dynamic way with which these institutions interact and the degree of connectivity and interdependence (both structural and complementarities)

between economic agents, the chapter deliberately uses the systems-of-innovation approach to examine the critical drivers of automobile and emissions policies in Malaysia.

The chapter presents an analytic framework, followed by an overview of Malaysia's automotive industry since its inception in the early 1980s. It then evaluates the consequences of the growing production and use of automobiles in Malaysia for the country's environment and energy policies, and reports on Malaysia's energy roadmap in hydrogen and fuel cells. It concludes with a number of policy considerations for the future.

## Framework of analysis

This chapter draws upon the systems-of-innovation literature to examine the promotion of automobile assembly and the state of environmental governance relating to the automobile industry in Malaysia (Mytelka, 2000). It looks at automobile policies alongside efforts to regulate emissions – both in the manufacturing of vehicles (e.g. catalytic converters and the development of hydrogen fuel-cell-powered engines) and in the use of vehicles after their sale.

Automobile assembly in Malaysia was initiated by Volvo in 1967, but domestic manufacturing took on a serious dimension following government efforts since 1985 to widen and deepen value added in the industry through the development of national companies. Despite the developing economy status of the country and the general lack of attention given to the environment, environmental issues have become increasingly important since the late 1990s. Although much of this can be argued to have arisen from international market pressures involving exports to developed markets, rapid expansion in domestic vehicle ownership is already dragging the country into a potentially dangerous environmental situation.

Within various agencies of government, discussions have thus begun on a number of different options to deal with these emerging problems. These include the incorporation of environment-friendly instruments in car manufacture, efforts to reduce personal vehicle use through the expansion of public transport and the development of environment-friendly fuels such as hydrogen. This chapter uses the systems-of-innovation framework to examine these developments and identify points in the system where injections of dynamism are needed to stimulate the absorption of best practices. Figure 12.1 provides a schematic representation of an innovation system. Because of gaps in Malaysia's policy framework, however, not all of the critical components noted in this figure are discussed in this chapter.



Figure 12.1 Innovation systems  
 Source: Mytelka (2000: 17).

Given the limited ability of civil society to translate its utility considerations into a sufficiently potent force for policy influence, more attention will be paid in this chapter to the role of government in promoting the development of the automobile industry in Malaysia. Nevertheless, owing to increased integration into the World Trade Organization (WTO) and the recognition that sustainable exports require adjustments to the manufacturing of local cars to meet, *inter alia*, environmental standards, the chapter does examine the drivers of environment-friendly instruments, albeit these instruments are largely still unlinked to car manufacturing. Also examined is the extent to which supplier networks, R&D institutions and their interface with clients and access to financial institutions have developed. In establishing the critical catalysts, the chapter evaluates the drivers of the automobile chain, including the sources of technical change. It addresses the market and the nature of learning specificity unique to such a scale-based heavy industry that has undergone substantial rationalization and global restructuring over the years. The

chapter also traces policy influences from the impact of related international agreements, such as the WTO Trade Related Investment Measures (TRIMS) agreement, the ASEAN Industrial Cooperation Scheme (AICO), the ASEAN Free Trade Area (AFTA) process and the WTO TRIPS agreement, on learning, innovation and competitiveness in the automobile industry.

The authoritarian nature of policymaking in Malaysia – especially from 1981 to 2003 – meant that the domestic constituency was not significantly consulted before a national car policy was formulated. Indeed, the government decided in 1981 to launch the Look East policy, which *inter alia* emphasized the development of heavy industries. International agreements in the early 1980s did not prohibit the use of local-content policy or differential treatment on the basis of ownership. Although such opportunities were closed to WTO members with a per capita annual income exceeding US\$1,000 which signed the TRIMs agreement in 2000, Malaysia managed to maintain its local-content policies by not signing the agreement.

Although no formal legal jurisdiction currently exists in the WTO on the legislation of environmental standards, many initiatives in this direction have already taken effect. In addition, national policies requiring more stringent controls on pollution have already required car manufacturers to reduce noise, carbon dioxide and particulate levels. Cars not meeting these standards have been banned from imports, notably into developed economy markets.

## Building a national automobile industry

The automotive industry in developing countries typically began with the assembly of completely knocked-down (CKD) parts into completely built-up (CBU) units. Manufacture of components and their subsequent assembly into CKDs came afterwards. To meet minimum scale-efficiency levels, latecomer economies promoting car assemblies – both national and foreign – started by raising tariffs on imports for domestic assemblers. In Brazil, Mexico, the Philippines, Thailand and South Africa the focus was or has been on promoting assemblies domestically without any limits imposed on ownership (Rasiah, 2003; Quadros, 2003; Ofreneo, 2003; Wood, 2003; Lara, 2002). In contrast, Malaysia, India, Indonesia and Korea have from time to time provided special support to national assemblers (Amsden, 1989; Prasada, 2003; Rasiah, 2001, 2005). Explicit promotion of national assemblers using the “carrot-and-stick” approach successfully contributed to the creation of internationally competitive assemblers in Korea (Amsden, 1989). While in many of these economies

the manufacture of auto components has risen to complement assembly activities, Taiwan has defied the old logic of assembly-led creation of backward linkages by becoming a major platform for the manufacture and export of auto components without significant assemblies within the island. In fact, Taiwanese manufacturers were the fourth-largest patent filer in auto parts in 2003 after the United States.

Like other latecomers, Malaysia was an importer of CBUs until import-substitution industrialization policies stimulated the start of assembly work by Volvo in 1967. It was not until 1981, when the Heavy Industries Corporation of Malaysia (HICOM) was formed, that government efforts to build national cars emerged. However, the first cars under the national umbrella only rolled out in 1985, and the initial cars were foreign made. Backward and forward linkages in the industry were expected to be created through a policy of technology agreements with foreign firms, localization and subsequently the acquisition of foreign automobile firms such as Lotus (UK).

Typically, automotive manufacturing in latecomer economies can be divided into four stages (Torri, 1991):

- import and sale of CBU automobiles
- assembly of imported CKD parts and localization of parts, which can be subdivided into three stages defined by technical level and market size for parts: local production of replacement parts or components; local production of original equipment manufacturer (OEM) parts for automotive assembly; and local production of major and functional parts (OEM), such as engine and transmission components
- local production of materials for cars and components
- local design of automotive bodies and other components.

Of significance in Malaysia was government investment in the first national automotive company, Proton. The company, launched among a series of heavy industry firms in 1981, was 70 per cent owned by the government-backed HICOM, while the remaining shares were taken up by two Japanese subsidiaries, Mitsubishi Corporation (MC) and Mitsubishi Motor Corporation (MMC), with 15 per cent equity each. In 1992 the company was listed on the Kuala Lumpur Stock Exchange (KLSE) and restructured as Perusahaan Otomobil Nasional Berhad (still using the same name, Proton). In December 1996 its shareholders were HICOM Holdings Berhad (with 26.0 per cent shareholding), Khazanah Nasional Berhad (16.50 per cent), MC (8.06 per cent), MMC (8.06 per cent) and other local and foreign investors with 41.38 per cent shareholding (Malaysia, 1998). The first two companies are owned and controlled by the government. Currently the largest shareholders in Proton are still government-controlled agencies, i.e. Khazanah Nasional Berhad (42.7 per cent), Employees Provident Fund (12.6 per cent) and Petronas (9.8

per cent). More recently Temasek Holdings, Singapore's investment arm, bought a 5 per cent share in Proton (*Malaysia Business*, 2005).

While the national industry enjoyed considerable government-backed insulation from competition, including from the WTO TRIMs agreement, the government had to accept deregulation initiatives under the AFTA agreement. Hence, the lowering of tariffs and the integration of assembly policies to be consistent with CBU and CKD conditions began in 2005 and are expected to be completed by 2008, by which time tariffs on car imports are expected to fall to 5 per cent. These initiatives have already reduced Proton's market share, though Perodua (an automotive company with two wholly owned subsidiaries set up to handle manufacturing and distribution activities) has retained its position in the domestic market (Mohamed and Kari, 2008). Whatever the future of national cars, figures for the period 1985–2003 show a continuous rise in sales in the country (see figs 12.2–12.4).

Whether national car policies continue or not, the liberalization of the industry has thus increased automobile sales in Malaysia – with foreign brands expected to rise in demand, especially after 2008. This rise will inevitably increase the pressure on the environment. The next section examines government emphasis on the environment and the policy instruments that address these points.

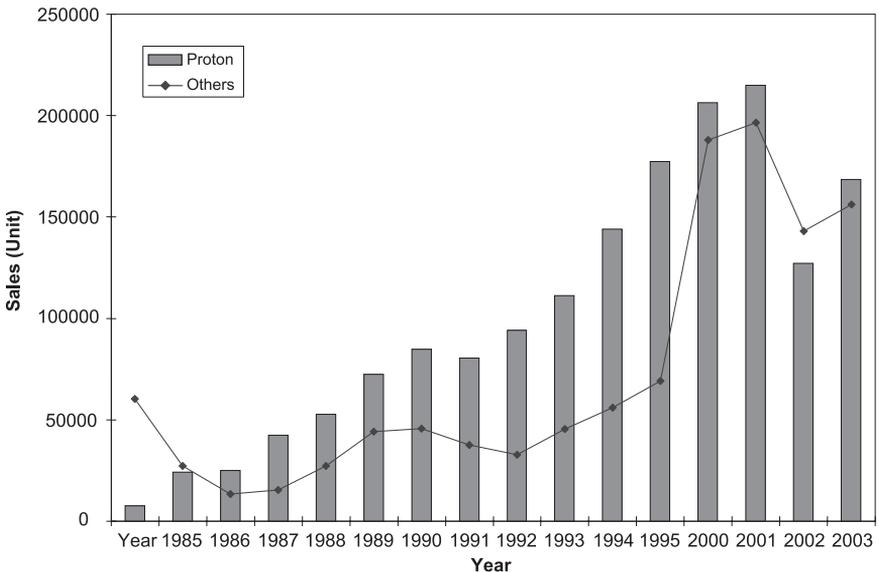


Figure 12.2 Car sales in the domestic market, Malaysia, 1985–2003

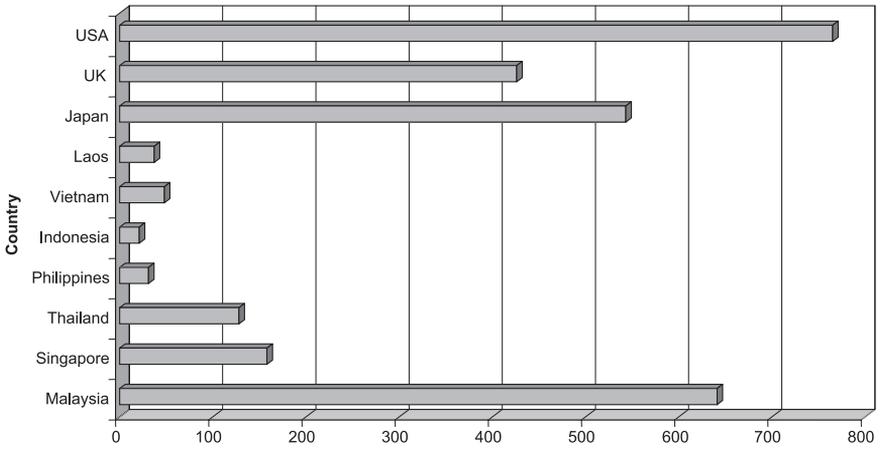


Figure 12.3 Car ownership per 1,000 population, selected economies, 2003

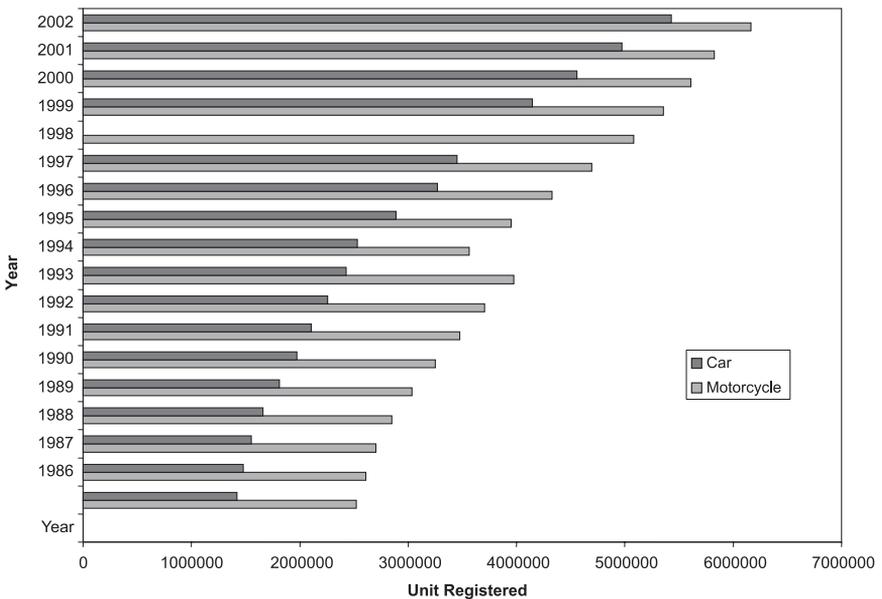


Figure 12.4 Cars and motorcycles registered, Malaysia, 1983–2003

## Environmental and energy governance

Environmental regulation in Malaysia can be traced back to British colonialism. The colonial government introduced environmental standards to ensure the orderly provision of mineral and agricultural resources to Europe. Environmental issues gained official importance in the Malaysian government following the promulgation of the Environment Quality Act (EQA) in 1974 (Rasiah, Szali and Abas, 2002). However, it was only in the second half of the 1980s that serious efforts were taken by the government to improve environmental standards in the country. In 1989 the government introduced financial incentives to encourage the use and treatment of environment-friendly technologies (Malaysia, 1995). Incentives to encourage the utilization of safe technologies to store toxic waste and other hazardous materials include “pioneer status” giving tax reductions over five years.<sup>1</sup> The proliferation of environment-friendly technologies was particularly important in the rubber and palm-oil industries, and fees paid for licensing dropped from 88 per cent to 44 per cent over the period 1977–1989 (Mohd Sham, 1992: 13, 15). The impact of this in the palm-oil industry is documented by Vincent and Rozali (1997). The government introduced preventive measures when it gazetted mandatory environmental impact assessment (EIA) studies to assist better environmental standards *ex ante* activity. Environmental audit procedures have also been adopted by a number of government bodies since the early 1990s (Gurmit, Soo and Chandran, 1993). The 1990s also saw the implementation of the ISO14000 series in the environmental arena and the adoption of more stringent controls by the Standards and Industrial Research Institute of Malaysia (SIRIM) on production and product technologies.

This section examines emission trends of selected pollutants against the background of environmental governance in Malaysia. The fundamental question posed is whether increased environmental legislation lowered emission levels. The effects of automobile manufacturing and vehicle use on environmental pollution will be examined after a discussion of the overall environmental emissions trend in Malaysia.

### *Trends in environmental quality*

Despite legislation and other policy interventions, emission levels rose for some air pollutants while falling for others. Emissions of most pollutants from industrial processes rose with rising industrialization from the mid-1980s. Carbon dioxide emissions rose at an annual average rate of 7.5 per cent in 1960–1997, the rise being highest in 1988–1997 (8.6 per cent). The emissions of *particulates*, *nitrogen dioxide* and *carbon monox-*

Table 12.1 Industrial emissions of pollutants, 1987–1997 (000 tonnes)

Year	Particulates	SO <sub>2</sub>	NO <sub>2</sub>	CO	Hydrocarbon
1987	10.4	54.1	25.9	4.7	3.0
1988	32.6	62.8	23.5	3.0	1.9
1989	21.8	31.8	22.5	2.1	1.4
1990	25.2	39.3	27.2	7.7	1.8
1991	23.2	33.8	27.7	5.8	5.6
1992	89.0	40.0	29.4	3.1	1.5
1993	101.2	43.1	31.2	3.5	1.6
1994	166.2	46.3	34.3	4.1	1.7
1995	103.5	109.2	41.0	5.1	2.4
1996	104.1	117.0	44.5	7.3	4.1
1997	55.1	142.2	51.1	8.4	3.6

Source: DOE (1999).

ide rose from 10,400, 25,900 and 4,700 tonnes respectively in 1987 to 25,200, 27,200 and 7,700 tonnes in 1990 (table 12.1). Emissions of *sulphur dioxide* and *hydrocarbons* fell from 54,100 and 3,000 tonnes in 1987 to 39,300 and 1,800 tonnes in 1990. There was an exceptional increase in particulates, sulphur dioxide and nitrogen dioxide recorded in 1988.

From table 12.1 it can be seen that air pollution levels increased considerably in the 1990s. Haze from fires and forest clearing caused serious eye problems and irritations in 1991–1994 and 1997. Emissions from industrial processes of particulates, sulphur dioxide, nitrogen dioxide, carbon monoxide and hydrocarbons rose to 104,100, 117,000, 44,500, 7,300 and 4,100 tonnes in 1996. While emissions of particulates fell sharply and hydrocarbons slightly in 1997, the rest have continued to rise.<sup>2</sup>

Against the background of these pollution trends, the rapid rise in vehicle sales in the country – the largest passenger-car market share in Southeast Asia – clearly highlights the potential for damage to be inflicted on the country (see fig. 12.4).

### *Regulating the transportation sector*

As in other developing countries, Malaysia has witnessed an explosive rise in the demand for transport vehicles in recent decades in conjunction with its rapid economic growth. The highest growth of urbanization and motorization was recorded in Kuala Lumpur and the Klang Valley: the rates of increase in car ownership are the highest in Kuala Lumpur compared to any other part of the country (Abd Rahman, 1997). Car ownership in the Klang Valley increased from 247 vehicles per 1,000 persons in 1990 to 546 and 994 vehicles per 1,000 persons in 1996 and 2002 respectively,

far beyond the national level per 1,000 population of 91 vehicles in 1990, 133 in 1996 and 210 vehicles in 2002 (Malaysia, 2004). A total of 8.5 million registered vehicles in 1997 accounted for emissions of 1.9 million tonnes of carbon monoxide (CO), 224,000 tonnes of nitrogen oxide (NO), 101,000 tonnes of hydrocarbons (HC), 36,000 tonnes of sulphur dioxide and 16,000 tonnes of particulate matter (PM) into the atmosphere.<sup>3</sup>

In 1993 a study on air quality management in the Klang Valley conducted by the Department of Environment (DOE) with the help of the Japanese International Cooperation Agency (JICA) warned that air pollution in urban areas would reach a critical stage by the year 2005 if steps were not taken to address it (JICA, 1993). The study highlighted that if Malaysia continues to ignore environmental emissions the pollution load will be heavier, and thereby more difficult and costly to manage. The report also noted that the emission of sulphur oxide from vehicles, factories and power plants would surge from 35,655 tonnes in 1992 to 51,999 tonnes by 2005. Assuming that 3.5 tonnes of pollutants are equivalent to a lorryload, the amount of sulphur oxide in the atmosphere by the year 2005 would reach 742 lorryloads. For other pollutants, if there was inaction then within 10 years nitrogen oxide emitted mainly by motor vehicles would swell from 54,472 to 115,308 tonnes, suspended particulate matter (fine dust) from 12,623 to 18,513, carbon monoxide from 290,407 to 659,223 and hydrocarbons from 73,455 to 166,720 tonnes.

The poor status of public transport has driven the demand for private transport. This can be observed by the increase in the percentage of trips using private vehicles, which rose significantly from 47 per cent in 1985 to 71 per cent in 2005, while the share of public transport dropped from 35 per cent to 16 per cent in the same period. The rising substitution of public transport with private transport is likely only to worsen the environment. There is growing concern about noise and atmospheric pollution, traffic congestion, accidents, energy use and conservation, and general environmental decay as a result of the excessive use of motor vehicles: their ubiquity has become a formidable threat to the natural environment and the quality of social and economic life. There is therefore an urgent need to slow down the growth in private transport. The concept of sustainable development as applied to the area of human mobility and transportation can only materialize when motorized transport is limited to serving the essential needs of society (Abd Rahman, 1997).

With the increase in car ownership, it was estimated that the demand for travel to central city areas would grow far beyond the capacity of the road network. The strong fleet growth as compared to low road network growth has resulted in rising vehicle-density ratios in Malaysia. The ratio reached 71 vehicles per road kilometre in 1999 as compared to only 46 vehicles in 1994, further intensifying traffic congestion. The difficulty of

constructing new roads and widening existing ones, especially in Kuala Lumpur, is already well known (Morikawa, Yamamoto and Dissanayake, 2003).

Apart from the transportation studies undertaken to manage the demand for travel in Kuala Lumpur, a structure plan has also been developed. The basic framework of a master plan study is the interaction between land use and transport. In 1982 the Federal Territory (Planning) Act was adopted, in which Kuala Lumpur City Hall was obliged to prepare structure and local plans for Kuala Lumpur. The structure plan established a broad policy framework for the planning of the federal territory over a 20-year period (Jamilah, 1992). This strategy called for the balanced development of Kuala Lumpur through moderate development within the city centre and much faster development in the outlying areas. The overall transport objective identified in the structure plan was to effect a 40–60 per cent shift from private to public transport, and the policy formulated in the plan is that a bus plus light-rail transit (LRT) network be adopted as the major public transport system to handle future traffic demands in Kuala Lumpur and its conurbation.<sup>4</sup> Construction of the LRT system was approved by the government in 1984.

In order to assist the master plan unit in formulating a set of transport programmes and policies that would complement the overall structure plan strategy for the development of Kuala Lumpur, the Kuala Lumpur Master Plan Transportation Study was conducted in 1981. According to Jamilah (*ibid.*), the study reiterated the need to restrain future traffic growth in the central core of the city, improve public transport services and provide priority movement of high-occupancy vehicles; it also recommended additional forms of mass transit. New roads and road improvement were recommended to provide accessibility to new growth centres (fig. 12.5).

Considerable effort went into these studies and their recommendations, and some of the proposals were implemented. The constraints, however, took many forms, including political, financial and operational (*ibid.*). One important caveat was the choice of measure to be implemented. Road building and improvement, for example, eases traffic in the short run, but generates new traffic in the longer term. The introduction of the rail-based public transport system in the 1980s failed to reduce the proliferation of private vehicle use. This might be due to a lack of integration at the system level between and within the various modes. Infrastructure projects such as the LRT and monorail are built without serious consideration of their role in the larger system. The multi-bus companies do not have efficient feeder services to the LRT system, although one of the LRT operators provided feeder bus services within a three-kilometre radius of its stations.

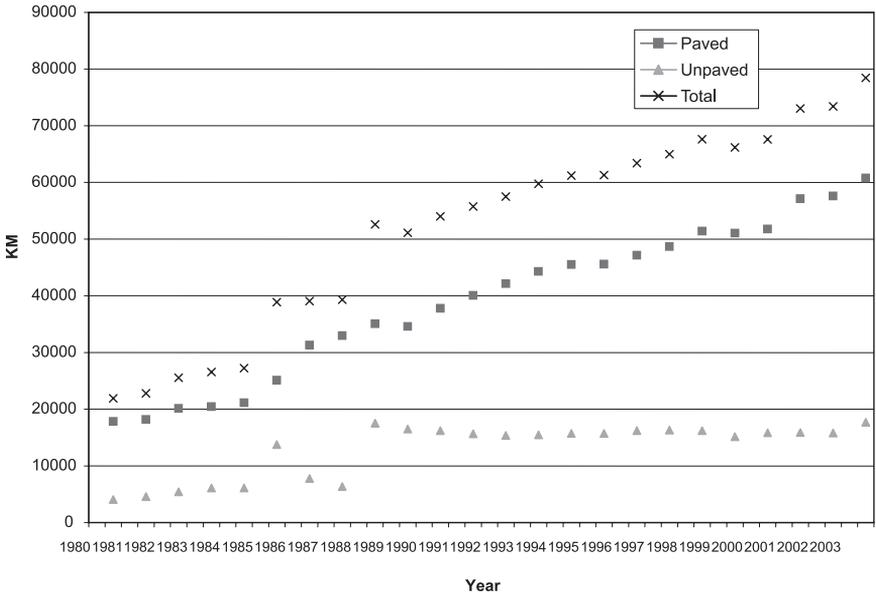


Figure 12.5 Road mileage (paved and unpaved), Malaysia, 1980–2003

There has recently been rising support for reconstructing the mass transport system in the Klang Valley to provide a comprehensive and efficient network. Public transport in the region will be regulated by the proposed Klang Valley Urban Transport Authority. The establishment of the proposed regulatory authority will be initiated by the steering committee of the Public Transport System in Klang Valley (INSPAK). The committee will undertake measures to increase the quality of the LRT and existing bus services. Physical integration will be implemented to improve connectivity in public transport terminals, as well as the use of the integrated ticketing and fare systems which the government believes will encourage the greater use of public transportation, thereby reducing traffic congestion (*New Straits Times*, 2004).

The question of how this will affect the transport behaviour of private vehicle users remains a pertinent issue. Will the countermeasure taken by the government to promote public transport be effective? Three important factors need to be addressed in answering this question. First is the extent to which predictions of demand are reliable. Second is the level of public acceptance. This requires careful estimation of the users' response to changes in prices and the characteristics of the services to be provided in terms of price and service elasticity. Lastly, the cheap fuel policy has a

reverse impact on sustainability of future resources and shapes the parameters within which decisions about using public transportation are made. Estimating these three conditions is crucially important as a guide for policymakers in choosing among alternatives.

### *Vehicle emissions plan*

Exacerbated by limited enforcement and the rapid urbanization rate in Malaysia, loopholes in addressing the air quality problem are related to the inadequacy of the present law to control vehicle emissions. The present regulation is confined to diesel-vehicle users, and car assemblers can get away with substandard engines. The Road Transport Department (RTD) is powerless to nab drivers of petrol-powered vehicles. The Motor Vehicles (Control of Smoke and Gas Emission) Rules 1977, which are enforced jointly by the RTD and the Department of Environment (DOE), are confined to diesel vehicles. This is a major setback considering there are 6.56 million petrol-driven vehicles on the road as against 626,622 diesel-powered vehicles.

The Ministry of Science, Technology and Environment (MOSTE) conceded in 1997 in a press statement by a senior official that it had been more than three years since the DOE proposed new regulations to curb excessive smoke emitted from diesel and petrol motor vehicles as well as motorcycles. With the exception of proposed control of emissions from diesel engines, which had been approved by the Attorney General's chambers, other proposed regulations to control emissions from petrol vehicles and motorcycles are still pending. What is urgently needed is a ruling and legislation to regulate vehicle assemblers to meet DOE emission standards before cars are allowed to be sold to consumers. Catalytic converters must be mandatory for all new cars. At present all cars locally assembled, including those made by Proton, Perodua, Toyota and Mercedes-Benz, are free from scrutiny. In the early 1990s the government proposed mandatory installation of catalytic converters to be fitted to the exhaust system of cars, which must be used with unleaded petrol under the Clean Air Action Plan. This proposal was initially scheduled for 1994 but was deferred when the car assemblers protested, citing high cost as the reason. Ultimately, such a failure is just a case of a lack of political will and scant public participation in the related political processes.

In light of the intricate and complex relationship between environmental degradation and the automotive sector, any effort to formulate an environmental action plan in Malaysia must include:

- emissions control whereby motorcycles with two-stroke engines are replaced with four-stroke ones for more efficient fuel combustion, and expediting changes in engine types to meet new emissions standards

- fuel control to increase the use of unleaded petrol and decrease the sulphur content in diesel
- traffic volume control by keeping tabs on the registration of new diesel vehicles and conducting periodic investigations on traffic volumes and patterns to determine the volume of pollutants generated by vehicles
- inspection and maintenance systems in which all vehicles are inspected biennially by the authorities to ensure fuel combustion is below the emission standard
- public education
- improvement in public transportation by introducing LRT and enhancing road networks to reduce traffic volume and lessen concentration of motor vehicles
- replacement of old, overused vehicles with new ones equipped with advanced combustion systems, and banning vehicles which fail to meet new emission standards
- promotion of the use of natural gas for power plants and vehicles.

### *Fuel diversification and the transport sector*

In light of the mounting problems arising from increasing pollution levels, the government adopted the Four Fuel Diversification Strategy in 1980 with a view to diversifying fuel use, notably towards the use of natural gas and renewable oils (e.g. biodiesel). In addition it directed research towards, and created a timeline for, the introduction of environment-friendly fuels – e.g. hydrogen and fuel cells. As a result of pressure from both users and vehicle makers, these policies have lacked follow-through despite the emergence of an action plan to drive the changes.

Crude oil and petroleum products, which comprised 87.9 per cent (2,374.4 pj) of final energy consumed in 1980, fell to 50.8 per cent by 2005 (see table 12.2). The supply of natural gas was increased from 7.5 per cent in 1980 to 39.9 per cent in 2005. Other energy sources such as hydroelectricity recorded a slight decline in share, from 4.1 per cent in 1980 to 3.4 per cent in 2005. Coal and coke, most of which was imported, recorded a significant increase from 0.8 per cent to 5.9 per cent in 2005. Energy supply saw an almost fivefold increase over the last 25 years (table 12.2).

Table 12.3, which looks at the fuel mix of commercial energy supply in Malaysia over the period 1990–2005, shows that the industrial and transport sectors dominate. The country's transport sector, moreover, has been and continues to be the least diversified in terms of fuel use: it remains highly dependent on petroleum and oil as the major energy source (table 12.4). More than 35 per cent of the country's oil use in 2005 went

Table 12.2 Final commercial energy supply by source, Malaysia, 1980–2005 (petajoule)

Source	1980	1990	2000	2005
Crude oil and petroleum products	344.4 (87.9%)	520.2 (71.4%)	888.4 (53.1%)	1,205.2 (50.8%)
Natural gas	29.2 (7.5%)	114.4 (15.7%)	622.2 (37.1)	948.4 (39.9%)
Hydro	16.0 (4.1%)	38.2 (5.3%)	73.0 (4.4%)	81.6 (3.4%)
Coal and coke	2.2 (0.8%)	55.5 (7.6%)	90.4 (5.4%)	139.6 (5.9%)
Total	391.8 (100%)	728.8 (100%)	1,674.0 (100%)	2,374.8 (100%)

Source: Malaysia Energy Centre (2005).

Table 12.3 Fuel mix of commercial energy supply, Malaysia, 1990–2005 (ktoe)

Sectors	1990	1998	2005 <sup>(e)</sup>
Industrial	5,885	10,121	14,564
Transport	5,387	9,793	13,674
Residential and commercial	1,646	3,315	6,451
Non-energy	299	2,093	2,985

Source: Malaysia Energy Centre (2005).

Note: e = estimate

Table 12.4 Fuel mix in the transportation sector, Malaysia, 1980–2005 (%)

Fuel	1980	1996	2000	2005 <sup>(e)</sup>
Petroleum products	100.00	99.94	95.4	93.2
Gas	0	0.06	4.2	7.8

Source: Malaysia Energy Centre (2005).

Note: e = estimate

to transportation, dominated by road travel. In the last four decades Malaysia's cheap gas policy has bred bad habits among motorists. The government introduced the "Go Gas" initiative in 1983, but achieved little success despite strong sales incentives.

While evolutionary economists allow the use of protection and subsidies to spawn technological capabilities among "infants" and provide equitable distribution, price distortions on fuel consumption have adversely affected the development of less-polluting fuels. Government failure has severely undermined energy policy in Malaysia. The government paid energy subsidies equivalent to around RM0.9 billion in the first six

months of 2004 (*The Edge Daily*, 2005), and this rose to RM6 billion in the financial year 2006–2007 (*New Straits Times*, 2007).

## Energy roadmap: Hydrogen and fuel cells

Knowledge-intensive, new-wave technologies are driving a revolutionary change in the automobile industry (Mytelka, 2004). In response to these changes, under the Seventh Malaysia Plan (1996–2000) the Ministry of Science, Technology and Environment through the intensive research priority area (IRPA) mechanism financed the first Malaysian fuel-cell project. The research programme is jointly run by two public universities, the National University of Malaysia (UKM) and the University of Technology of Malaysia (UTM), each of which has been assigned primary research tasks related to the development of components of hydrogen fuel cells as part of a future roadmap for the development, testing and application of hydrogen and fuel cells in the Malaysian transport and energy sectors.

UKM was given the task to develop:

- fabrication of membrane electrolyte assembly and bipolar plates
- hydrogen production from methanol
- hydrogen production from solar energy
- design and fabrication of fuel-cell stacks.

UTM researchers were asked to focus on:

- fabrication of new polymer electrolyte membranes
- hydrogen storage on metal hydrides
- control system and power conditioner.

Under the Eighth Malaysia Plan (2002–2007), both institutions were awarded a RM30 million grant from the Ministry of Science, Technology and Innovation (MOSTI) through the IRPA mechanism to move from components to the development of fuel-cell technologies. Their research has already produced some early results.

A tricycle prototype powered by a 300 W proton-exchange-membrane fuel cell (PEMFC) using hydrogen, for example, was developed and rigorously tested under different road conditions. The actual performance followed closely the design performance. Maximum speed is 40 km/hr, fuel consumption is greater than 800 km/gallon of gasoline equivalent and fuel capacity is 900 km. The tricycle is used to calibrate a new fuel-cell engine simulator developed by the UTM fuel-cell research group. The simulator was used by UTM in the design of the H2Motive, a fuel-cell-powered scooter developed as a means to demonstrate the technical and economic viability of a 7 kW fuel-cell engine powered by hydrogen. Its power-train consists of PEMFC stacks and a traction battery. The

direct-drive train uses a permanent magnet motor with regenerative braking capability. The scooter was ready for road testing in 2005.

In addition to the development of fuel-cell vehicles, work is under way on a variety of means to generate hydrogen, and demonstration projects to enhance public awareness are also being carried out. The solar-hydrogen eco-house is one example. Solar energy is used by a PV panel to generate 5 kW electricity for lighting and an electrolysis process using a PEMFC to generate 0.54 m<sup>3</sup>/hr hydrogen as clean fuel for cooking and hot-water uses. Stored hydrogen is also used by the PEMFC at night for electricity generation. Excess electricity is connected to the grid.

These projects find their successors in the content and recommendations of Malaysia's interim framework document on hydrogen fuel-cell (HFC) technologies produced by the Malaysian Energy Centre (MEC), the Economic Planning Unit (EPU) and the Ministry of Science, Technology and Innovation. The contents of this framework cover several broad policy areas (table 12.5):

- financial and funding
- capacity building and awareness
- standards and policy development
- technology development, R&D, cost competitiveness and market enhancement.

Within this framework, a work programme for research, development and demonstration over the period 2005–2014 was drawn up and some elements of the programme have been initiated (table 12.6).

Malaysia is also an active partner in the Asia Pacific Economic Cooperation (APEC) Energy Working Group (EWG). Within its work programme, the EWG is identifying opportunities for hydrogen and fuel-cell development in the region as well as sharing information and experiences emerging from the range of hydrogen policies and programmes already in place in member economies. It is also exploring avenues for cooperation with the International Energy Agency (IEA) and the International Partnership for the Hydrogen Economy (IPHE), and developing a programme for capacity-building assistance on policy and regulatory issues. Over the longer term the EWG is working towards harmonized codes, standards and regulations.

The APEC EWG also developed an interim framework document, which was presented to APEC energy ministers at their meeting in Manila on 10 June 2004. The interim framework was developed as a means to obtain general agreement on the first steps APEC economies could take to support hydrogen and fuel-cell development, recommending a priority list of potential activities that would help create this foundation. It is also designed to identify competitive advantages for participating countries as both users and producers of hydrogen technologies. The

Table 12.5 Government programmes to develop hydrogen fuel-cell technology, 2005–2014

<i>Financial and funding</i>		
Government incentives	Availability of incentives to technology suppliers (2010)	2008–2014
Establishing new funding sources	Availability of Venture Capitalist Fund (2006) Five financial institutions provide soft loans for company start-ups	Approval of RM100 million loan for start-up of 10 companies (2008) Participation of 15 venture capitalists in the fund scheme
Establishing viable financing mechanisms	Strengthened Credit Guarantee Corporation mechanism	Quantifiable guidelines for financing available Approval of 15 proposals under strengthened Credit Guarantee Corporation mechanism
<i>Capacity building and awareness</i>		
Training and capacity-building programme	Increase number of professionals in international associations Local experts trained and retained Establishment of Hydrogen Energy Consortium	Improvement of local competency
Incorporate hydrogen and fuel-cell syllabus in education system	Fuel-cell kits for core curriculum are established Postgraduate courses in universities available	
Demonstration of hydrogen-fuel vehicles		Demonstration of hydrogen-fuelled vehicles and fuelling stations Set up demonstration and exhibition at National Science Centre
Dissemination of information, developing networks and collaborations	Availability of national hydrogen and fuel-cells database Information exchange services established Website created Focal point/coordinating body appointed	Establishment of mobile learning centre Increase in public sector interest

Table 12.5 (cont.)

<i>Standards and policy development</i>		
Establishment of working group for standards and policy development	Join international working groups for standards development	
Establishing standards, regulation and policy	Sixth fuel policy established	Study of local and international regulatory frameworks Policies on hydrogen application to include gazette regulation and requirement that every installation have 1 MW PEMFC as back-up power Established standards and special tariff

Table 12.6 Malaysian government hydrogen fuel-cell research, development and demonstration programme, 2005–2014

<p>Research in photochemical cells completed by 2005  Photovoltaic (PV) hydrogen production demonstration system  PV-wind hydrogen production demonstration system  Hybrid hydrogen/gas line internal-combustion engine (ICE) tested  Storage and production technology developed (carbon nanostructure)  Development of hybrid fuel cell/ICE  Prototype of photoelectric chemical system  Development of 1 kW PEMFC prototype  Development of indigenous PEMFC component technologies, e.g. PEM, membrane electrode assembly (MEA), bipolar plate  Development of 5 kW PEMFC prototype  Development of 5 kW PEMFC-powered bus air-conditioner  Development of 10 kW PEMFC system building  Development of advance PEMFC cell component technologies (non-hydrated PEM, carbon nanotube electrode and metal foam bipolar)  Development of four 10 W direct-methanol micro-FC prototypes for mobile phones  Development of 50 kW PEMFC-powered private car prototype  Development of 50 kW PEMFC prototype for automobiles</p>
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Source: Malaysian Energy Centre (2005).

region has strong manufacturing capabilities and in particular has close links with the automobile sector, from which significant demand for fuel cells and other hydrogen technologies may originate. In addition, many of the APEC economies are already world leaders in hydrogen and fuel-cell technologies.

Three of the areas in Malaysia's HFC roadmap – education, outreach and information dissemination; safety, codes and standards; and capacity-building assistance – are being developed within the context of this regional cooperation framework. APEC forums on energy, for example, have actively discussed ideas to facilitate outreach to policymakers, industry and the general public about the life-cycle costs, benefits and safety considerations of the hydrogen economy, including web-based information tools, policy forums and training workshops. Recognizing that harmonization of codes, standards and regulations can help to reduce barriers to trade and the development of hydrogen technologies, APEC forums have continued to discuss the development of codes and standards and have held workshops to identify standards gaps. This work will build on a current APEC project to develop a codes and standards sourcebook, which will serve as the baseline for future discussions within APEC. In the area of capacity building, suggestions include information sharing with other international organizations, including the IPHE and the IEA, establishing APEC hydrogen test-beds and online sharing of information and expertise.

In response to the 2004 meeting, the government of Malaysia has initiated policies to begin diversifying energy resources. As part of this plan, Malaysia is now considering hydrogen as a potential future fuel and funding has been directed to related institutions for a hydrogen R&D programme. One of the initiatives that have resulted from this funding was the establishment of the National Institute of Fuel Cells in UKM. Research undertaken at this institution is conducted as UKM-UTM collaborative projects. Although Malaysia has yet to launch any hydrogen demonstration projects, there are currently a number of ongoing hydrogen R&D activities. Recently a workshop was convened to gather inputs from both government and private sector perspectives on the development of new energy sources, including hydrogen. This workshop was, in part, meant to serve as an opportunity to develop an overview of future hydrogen energy development activities within the country (see [www.aseanenergy.org/pressea/news/n\\_malaysia/news\\_my\\_11.htm](http://www.aseanenergy.org/pressea/news/n_malaysia/news_my_11.htm)).

## Conclusions

This chapter examines the development of environment-friendly automobile policies in Malaysia using the systems-of-innovation approach. Ma-

Malaysia is a rare example of a latecomer that has retained its national car development policies, although liberalization initiatives are threatening a shakeout among the domestic participants. Malaysia's national car policy succeeded in producing Malaysian-designed cars, especially under Proton. Extensive focus on national car development without an equally proactive emphasis on technological capability building – including in environment-friendly technologies that are essential to supporting car sales in developed car markets – has meant that environmental policies in the country have not responded effectively to check pollution. Liberalization trends – especially following the inclusion of automobiles in the AFTA process since 2005 – have stimulated an increase rather than a drop in car demand. Rising car sales threaten to wreak further havoc on the country's environment.

The lack of integration between vehicle manufacturing and sales, transport policy and environmental policy raises serious problems for the process of development in the country. Despite the growth in LRT networks, public transport has done little to relieve vehicle-use pressures in the bigger cities in Malaysia. The government's lack of emphasis on vehicle emission levels, in not requiring the use of at least catalytic converters, has only aggravated air pollution further. Yet the manufacturers already have the capabilities to equip vehicles with catalytic converters, as seen from the sales in export markets.

There is thus growing public concern over noise and atmospheric pollution, traffic congestion, accidents, energy use and conservation and general environmental decay as a result of the excessive use of motor vehicles. In Kuala Lumpur alone, the number of vehicles increased 200 per cent over the period 1995–2005 while the city's road networks only expanded half as fast. Currently, more than 35 per cent of the country's oil use goes to the transportation sector, which is dominated by road travel. Heavy petroleum and gas subsidies have bred negative perceptions among motorists. With little effort made to raise awareness among the public about the dangers of emissions, efforts to reduce subsidies on energy sales since 2005 have brought ugly protests among consumers. Policies, strategies, legislation and enforcement are inadequate.

In short, it can be seen that a number of initiatives have been taken at the policy level to address environmental issues in Malaysia, including efforts to frame strategies to reduce vehicle emissions. However, these have encountered serious problems of enforcement. It is quite puzzling that manufacturers have lobbied to reduce the use of environment-friendly gadgets in cars sold in the country. The costs involved in installing environment-friendly devices, even if only end-of-pipe solutions such as catalytic converters, are marginal since the scale and volume necessary to appropriate the R&D costs have already been met following the

mandatory use of these items in the developed economies. As a late-comer, Malaysia should learn from the existing examples at a faster rate and implement environment-friendly policies. Serious efforts should thus be made to implement the energy roadmap. Unless these initiatives are taken quickly the country is likely to be overtaken in the development ladder by economies currently lying below it.

The Malaysian government, moreover, must focus more concertedly on environmental management if it is to avert a potentially disastrous environmental calamity. In addition to enforcing existing environmental legislation in order to reduce environmental emissions, the HFC roadmap must be regarded more seriously with a view to its rapid implementation. This will require not only sustained efforts to substitute existing technologies with cleaner ones, but also new initiatives designed to expand the use of public transport in the country.

## Notes

1. Firms directly involved in storage, treatment and disposal of toxic and hazardous waste in an integrated manner can apply for "pioneer status". Companies generating waste can establish facilities to store, treat and dispose of it, either on site or off site, and are then eligible for a special allowance at an initial rate of 40 per cent for one year and an annual rate of 20 per cent of capital expenditure in the next four years (Malaysia, 1995). Firms can access duty drawbacks on machinery involved in storage, treatment and disposal activities. Foreign firms have the same rights and regulations on environmental standards as local firms.
2. In addition to rapid industrialization, it is possible that part of the rise in recorded air pollution levels could be due to improved measurement coverage and instruments used in the 1990s.
3. Emission of smoke and gaseous pollutants such as carbon monoxide, hydrocarbons, oxides of nitrogen and particulate matters emitted from motor vehicle exhausts are controlled under the Environmental Quality (Control of Emission from Diesel Engines) Regulations 1996 and the Environmental Quality (Control of Emission from Petrol Engines) Regulations 1996.
4. See chapter 8 in this volume for the corresponding efforts by Egypt to deal with pollution generated by road transportation in the Cairo area.

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Part IV

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Strategies and roadmaps

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# Introduction

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A critical point of departure in thinking about hydrogen strategies and roadmaps is the uncertainty that continues to surround the notion of an emerging hydrogen economy. Government strategies and funding policies with regard to the development of clean hydrogen, hydrogen fuel cells and alternative fuels have been in flux over the past 10 years, and frequently move in opposite directions. A recent example of this is the US Department of Energy's proposed 2009 budget request for its Office of Energy Efficiency and Renewable Energy. This proposal eliminates funding for renewable hydrogen production and for research and development leading to manufacturing. It also cuts in half the funding request for fuel-cell vehicle validation. In contrast, the European Union's new Strategic Energy Technology Plan (SET-Plan) contains proposals for joint technology initiatives that would focus precisely on the development phase of new technologies with a view to their commercialization. One of these deals with fuel cells and hydrogen.

Adding to the uncertainties resulting from policy changes is the high cost of hydrogen and fuel cells relative to alternatives. Although there is general agreement that costs are coming down, no dominant design has yet emerged for hydrogen fuel-cell vehicles and there remains a lack of consensus on when commercialization might take place.

Faced with rising CO<sub>2</sub> emissions, a wide range of choices in alternative fuels and vehicles has emerged. This, too, creates difficulties in designing strategies and roadmaps for countries in the South that do not have the resources to move in multiple directions at once. They must make

choices, and must do so under relatively high levels of uncertainty. Acknowledging these difficulties, however, does not mean that thinking about transitions to new technologies in the transport sector can simply be postponed.

This is all the more important for developing countries, as rising levels of greenhouse gases (GHGs) become an issue in the provision of energy more generally. Along with the processes of industrialization and urbanization have come dramatic changes in consumption patterns that are leading to an intensification of energy use. We saw this problem in the substantial increase in private automobile ownership, but it is also emerging in energy-intensive agricultural production to support the demand for meat and in the building sector for heat and cooling. A large number of developed and developing countries are currently concerned about rising levels of energy consumption and the need to ensure the provision of electricity to urban as well as off-grid areas. In the absence of new technologies, many of these countries will fall back on older solutions with a larger carbon footprint, such as coal-fired plants.

There is thus a need to go beyond a focus solely on transport to consider hydrogen fuel cells and alternatives in both energy and transport sectors. In looking at hydrogen strategies and roadmaps, the chapters in Part IV move in this direction.

Developing forward-looking strategies for hydrogen and alternatives at the national level, they argue, will require a broad-based consensus on longer-term goals and the pathways by which these can be reached. In the Netherlands, for example, the focus is on long-term policies aimed at achieving a sustainable energy economy. Realizing such an economy, however, requires new ways of thinking and doing. This has led to a shift away from simply identifying individual objectives to creating processes through which awareness of issues and opportunities, consensus building and collaborative partnerships can structure transition pathways.

South Africa has taken a similar approach in developing a process of dialogue leading to the adoption of its National Hydrogen and Fuel Cell Technologies Research, Development and Innovation Strategy. Brazil and South Africa have also stressed the need to develop pathways that position their countries for multiple technological futures, enable the building of local technological capacity and promote equity and inclusion as well as sustainability.

Although the goals in a hydrogen strategy may be long term, the starting point is often an analysis of what resources are locally available and what role these can play in creating new pathways for the future – an approach pursued in Iceland, Nigeria and South Africa. In some cases this is complemented by a conscious effort to situate the discussion of hydrogen and fuel cells within a broader “transport system” (Egypt, Ice-

land) or “sustainable energy system” (Netherlands) framework that is used to explore alternative ways of diversifying energy portfolios and approaches to transport needs. In others, the focus is on ways to strengthen the local knowledge base and build production capacity in hydrogen (South Africa), fuel cells (Canada) or fuel-cell vehicles (China). By combining energy and transport considerations in their strategies, the Malaysian, South African and Dutch cases bring to this volume information on the use of hydrogen fuel cells for stationary power in off-grid rural areas and back-up power in, for example, hospitals (South Africa). The concluding chapter draws upon these various experiences to identify key elements in the process of managing a transition under conditions of uncertainty.

# 13

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## Transition to hydrogen and fuel cells

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*Remco Hoogma*

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### Introduction

Public debate about hydrogen and fuel-cell technology takes place between two extremes: it is perceived as the immediate answer to all questions related to air pollution and noise, climate change and expensive fuels, but also as too dangerous even to think about. In contrast, Dutch policy is rather silent about these technologies. There are obligatory references to hydrogen as the energy carrier of the (far) future, but the option hardly features in the policy debates about the above-mentioned issues. The problem for hydrogen and fuel cells is that they are good for many policy objectives – air quality, climate change, security of energy supply, competitiveness/innovation – but not the best solution for any of them in the short term. In a sports analogy, hydrogen and fuel cells are much like the decathlete: the technology is a good all-rounder. In another analogy it is the *homo universalis* or “Renaissance man”, but not an optimal specialist.

The Netherlands has started to develop long-term policy aimed at achieving a sustainable energy system, called the “energy transition” process. Hydrogen and fuel cells are finding a place here. This chapter presents the energy transition policy up to mid-2006, discusses the place and role of hydrogen and fuel cells in energy transition (drivers and barriers) and presents a plausible introduction path for hydrogen and fuel cells in the Netherlands.

## Energy transition: Towards a sustainable energy system

Dutch energy policy aims to realize a sustainable energy economy for three basic reasons. For oil the Netherlands depends almost entirely on imports from countries outside the European Union. This makes the country vulnerable – especially the transport system, which is dominated by use of mineral oil products. Thanks to domestic natural gas resources the dependence on gas is less pressing, but these resources will run out in the next few decades. Then there are the negative environmental effects associated with using fossil fuels and the increasing cost of energy. These aspects force the country to think about its energy economy. The stated objective is that the Netherlands will have a sustainable energy system within 50 years. Energy should be affordable, continuously available and clean. In a sustainable energy system, energy demand would be reduced, renewable sources would be dominant and the system's emissions would be no more than the uptake capacity of the ecosystem, while comfort for consumers would be maintained.

Realizing a sustainable energy economy requires a new way of thinking and acting, drawing together competencies from various disciplines. The Netherlands has initiated the process of energy transition (Ministry of Economic Affairs, 2004), and the government actively seeks public-private cooperation through the launch of several energy transition platforms involving collaboration between civic organizations, scientists, the government and companies working on alternative sources of energy. This collaboration results in vision, strategy, policy and innovative projects. Socially responsible entrepreneurship and healthy profits are important aspects of this process. The government role is to facilitate and enable a conducive policy environment: finance, removal of institutional blocks, creation of support networks, etc. Six departments have come together in an interdepartmental directorate for the energy transition programme. A task force for energy transition consisting of CEOs of major Dutch firms and institutes acts as watchdog for the process and provides advice on how the government can improve conditions for change.

Energy transition is inspired by research on system innovations and technological regime shifts and transitions. These terms all refer to important shifts in functional systems involving multilevel alterations through which society, or an important societal subsystem, fundamentally changes (Kemp, 1997; Hoogma et al., 2002; Hoogma, Weber and Elzen, 2005). Examples of past transitions are the moves from coal to natural gas for residential heating and electric power (in the Netherlands), from horse and carriage to the automobile and from the telegraph to telephone and internet. These processes took decades and involved changes

at institutional, social, economic, ecological, technological and policy levels. In the late 1990s the Netherlands came to the conclusion that such fundamental changes are needed to solve persistent problems in the field of sustainability related to energy, biodiversity and use of natural resources, agriculture and mobility. With the sustainability challenge, the government decided to give the new approach of “transition management” a chance. This is not a planning process, but rather a heuristic process with some key elements: anticipation of future developments, developing visions and strategy in public-private discussions, learning by doing through experiments and adaptation of vision, strategy and policy based on lessons learnt (Rotmans, 2003).

### *Taking advantage of opportunities*

The approach of energy transition is pragmatic, concrete and makes use of the possibilities available in the Netherlands, in both the short and the long term. The approach takes into account that changes are not only necessary but also create opportunities for innovation and economic growth. The Netherlands has many opportunities to make the transition to clean, affordable and reliable energy. The country has a unique combination of strengths and opportunities: strategic oil and gas reserves and developed capabilities, related oil and gas industries, petrochemical industries, its geographic position, advanced agriculture and supporting transport and logistics infrastructure. Challenges such as air quality, traffic congestion and high energy prices provide impetus to resolve these problems through more sustainable energy technology. The country is ideally located and resourced to become the centre of the north-west European gas hub, and a leader in bio-energy handling, production and trading. There is also well-developed industrial hydrogen infrastructure in the Rijnmond area near Rotterdam, which could be expanded for other uses (Royston, 2005). Energy transition combines this expertise and resources to realize sustainable energy in concrete projects. By focusing on national strengths, the country can take advantage of economic opportunities and improve its competitive position. Dutch firms can benefit from knowledge creation and economic opportunities that arise from exploiting new technology.

### Main themes of energy transition

The participants in energy transition have established six themes, each championed by a public-private platform. The platforms are assigned

Table 13.1 Six themes of energy transition

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- *Green raw materials.* Activities in agriculture, processing agricultural raw materials and in the chemical industry provide an ideal starting point for using plant-based raw materials in industrial processes, such as in the manufacture of biofuels and bioplastics.
  - *Sustainable mobility.* The aim is to accelerate the market introduction of alternative motor fuels, such as natural gas, biofuels and hydrogen, along with new, environmentally clean vehicles. The focus is also on vehicle guidance systems to streamline traffic and prevent traffic jams.
  - *Chain efficiency.* Dutch industry has a head start in efficiency as a result of long-term cooperation between the business community and government. By means of more intelligent organization of production chains, industry can become even more energy efficient.
  - *New gas.* To conserve national gas resources, the Netherlands is looking for more efficient applications of natural gas in horticultural and housing sectors. Possibilities of biogas and hydrogen are investigated, as well as clean applications for fossil fuels with CO<sub>2</sub> capture.
  - *Sustainable electricity.* This involves the development of new, clean and reliable sources of electricity, such as offshore wind energy and energy from biomass. The Netherlands has a strong logistics network and a beneficial location for refining and using fuels.
  - *Energy use in the built environment.* Almost 20 per cent of energy in the Netherlands is used for heating and cooling buildings. Insulation can reduce this energy consumption to near zero, and the sun and the earth (geothermal) can supply all remaining energy needs.
- 

the task of developing a vision and strategy. Unlike the EU technology platforms, they cover application areas/themes rather than technology fields. Public-private consortia conduct experiments based on these themes to ensure that the final aims become clear and feasible. Companies, scientific and civic organizations and government agencies are thus working together on these six themes (table 13.1):

- green raw materials
- sustainable mobility
- chain efficiency
- new gas
- sustainable electricity
- energy use in the built environment.

The public-private platforms have identified the most promising transition pathways for each of the six themes. Transition pathways are defined as a consistent ensemble of actions, fulfilled conditions and learning experiences that lead to the realization of a stated ambition. This portfolio is dynamic, in the sense that pathways may be discarded and new ones added when new information becomes available from experiments or

Table 13.2 Transition paths for the six energy transition themes

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*Theme: New gas*

- Energy conservation in the built environment
- Mini-CHP and micro-CHP (decentralized energy generation)
- Energy conservation in horticulture
- Clean natural gas (CO<sub>2</sub> capture and sequestration, “clean fossil”)
- Green gas (biogas and gasified biomass, hydrogen)

*Theme: Sustainable mobility*

- Hybridization of the vehicle fleet
- Biofuels for transportation
- Hydrogen for transportation
- Intelligent transport systems – mass individualization of automobility

*Theme: Green raw materials*

- Sustainable production and refining of biomass
- Certification of the biofuels import chain
- Co-production of chemicals, transportation biofuels, electricity and heat
- Innovative use of green raw materials and greening existing products and processes in the chemical industry
- SNG (synthetic natural gas) in the natural gas infrastructure

*Theme: Chain efficiency*

- Precision agriculture
- Process intensification
- Clearing house bulk products
- From centralized to decentralized (including process intensification)
- Waste
- Combined heat and power
- Co-siting and waste heat
- Sustainable paper industry

*Theme: Sustainable electricity supply*

- Increasing the share of renewable energy sources
- Use of combined heat and power
- Decarbonization of central power generation
- Networks

*Theme: Energy use in the built environment*

- Started in 2006
  - Will develop some of the paths of the other themes
- 

when long-term market circumstances change, e.g. availability of feedstock. The portfolio comprises some pathways that will be competing for the same feedstock, the same infrastructure or at least the same funds. The current portfolio consists of 26 pathways (table 13.2), down from over 80 in a previous phase in energy transition. Discussions are ongoing about whether to make a further selection to focus attention and funding, or whether first to gather experience for the different pathways. The task

force for energy transition calls for starting gathering experience in the different pathways (see below).

### *Critique of energy transition*

Late in 2004 the Council for Housing, Spatial Planning and Environment and the General Energy Council of the Netherlands (2004) published a joint advisory on the energy transition process. While acknowledging that the process had a good start, they pointed to several aspects that needed strengthening. Their basic critique was that energy transition was thus far a “niche process” without much impact on wider policy and business strategies. Innovation, energy and sustainability policy remained largely separate, rarely intersecting in the energy transition process. Politicians lacked a sense of urgency about the need for a sustainable energy system – but this has changed since President Putin closed the natural gas pipeline to Ukraine. Collaboration between departments in energy transition was insufficient. The process was also considered to have too much national focus and lacked an international dimension. Finally, the advisory called for the drafting of a national energy transition action plan.

There are other critiques as well. Energy transition is considered by some as one big talking shop where old-boy networks are continued and large companies are in key positions to delay or control the pace of transition to benefit their vested interests. Time and money are spent on talk – defining visions and strategies – rather than on demonstration projects that provide lessons from practice about what works and what does not. The claim is that the discussions hardly lead to new insights, as each participant promotes its self-interest. Old project ideas are recycled as possible energy transition projects. The democratic nature of the process is also questioned, even though it is open to participation by various stakeholders.

There is also concern that the strengths of the Netherlands, especially its strong position in gas and oil refining, could provide lock-in. There is frustration that progress in energy transition is slow when it comes to making investments in actual production facilities and infrastructure, and that investments and knowledge creation are taking place elsewhere in Europe where other governments have made clearer long-term commitments and reduced the risks of investment (Royston, 2005). Another line of criticism is that energy transition is too technology dominated. System change, it is argued, has more to do with changes in consumer behaviour and organization of the market and government than with developing new technologies. There is thus a need for socio-economic research and monitoring to learn about how transitions actually happen rather than demonstration projects for individual technologies.

### *Transition Action Plan*

In May 2006 the task force for energy transition published the national Transition Action Plan. The key message is that the Netherlands should strive to be an international leader in warding off the threats associated with the prosperous world's use of fossil raw materials for its energy supply. This high ambition requires a focused national strategy and mobilization of ingenuity, entrepreneurship and means. It implies a break from the recent past, when the Netherlands was a follower of Brussels in energy policy (e.g. in liberalization of the energy system) rather than a leader.

The portfolio of transition pathways is the core of the action plan. The choice for the portfolio sends three messages, according to the task force. First, it is realistic to keep options open as there is no simple solution to the world's energy problems. Second, the Netherlands should choose the pathways best suited to the country's strengths and industrial opportunities. Third, this approach stresses that a long-term perspective needs to be taken. With continuous economic growth, the plan will lead to a 50 per cent reduction in CO<sub>2</sub> emissions in 2050 compared to the 1990 level, annual energy savings of 1.5 per cent and progressively more sustainable energy systems between today and 2050. The task force calls for government support for the transition pathways via coherent, consistent and continuous long-term policy by subsequent cabinets (Task Force for Energy Transition, 2006).

The government welcomed the Transition Action Plan and started procedures to allocate €250 million (for a period of four to five years) to a number of energy transition experiments, funded by the windfall profits from Dutch natural gas.

### Hydrogen in the Netherlands

It should be clear from the above that hydrogen is considered as only one potential option in the transition pathways portfolio. The most visible is hydrogen as a transportation fuel, but it also features in other themes. Hydrogen is considered in the pathways of green gas (as a final product, but also as an intermediate step in the production of synthetic natural gas), and "clean fossil" could include production of hydrogen for electric power from natural gas or coal with carbon sequestration. Hydrogen is also part of several routes of co-production of green raw materials, transportation biofuels, electricity and/or heat, as well as a semi-product or raw material in various industrial processes which could possibly be linked and optimized for better chain efficiency. And finally hydrogen produced from surplus wind energy could play a role in net balancing

and load management for the electric power grid. At the time of writing, the discussion in energy transition about the role(s) of hydrogen in the future energy system had not yet matured. A working group on hydrogen is drafting a vision and strategy.

Several ongoing research projects feed into these discussions, and it is often the same persons or at least organizations that take part. HyWays ([www.hyways.de](http://www.hyways.de)) is an integrated project in the European Sixth Framework which is developing a European roadmap for hydrogen using a combined approach of consensus-oriented stakeholder discussions and modelling of economic, environmental and employment effects. The consortium consists mainly of industrial companies (automotive, energy, equipment), representatives of European countries, including the Netherlands, and research institutes. Most of the Dutch stakeholders are involved in vision building for the Netherlands. Largely the same group of stakeholders is also involved in a parallel project of the Environmental Institute of the Free University of Amsterdam, the Dialogue on Hydrogen ([www.h2dialog.nl](http://www.h2dialog.nl)). This project entails a participative enquiry into institutional strategies to foster the transition to a hydrogen economy. "Dialogue groups" of stakeholders develop strategies for three approaches: admixture of hydrogen to the natural gas grid and on-site hydrogen production for industry; hydrogen for transportation combined with fuel cells or other conversion technology; and decentralized production of sustainable hydrogen in the built environment.

Another major research project is "Greening of Gas", which studies the possibilities and conditions for admixture of hydrogen to the natural gas grid as a possible transition pathway for hydrogen. The project focuses on end use of the mixture in residential heating and industrial furnaces. The European "extension" of this is the integrated project NaturalHy, which has the same objective but explicitly looks at the possibilities to inject hydrogen in the natural gas grid and extract it again for use in pure form, in fuel cells for instance. Finally there are a number of smaller R&D projects for the development of hydrogen-related equipment, such as fuel cells. There is currently no specific hydrogen and fuel-cells programme in the Netherlands, but the topic is welcomed in several innovation and energy programmes.

## Drivers and barriers

One way of analysing the discussion about hydrogen as an energy carrier in the Netherlands is to look at drivers and barriers. Several drivers consistently stand out in the hydrogen futures literature: air quality, climate change, security of energy supply and competitiveness/innovation. And the outstanding barriers are the absence of a hydrogen infrastructure,

high costs, especially of fuel cells and sustainable hydrogen production, and technological immaturity (hydrogen on-board storage, limited range, lifetime of fuel cells) (McDowall and Eames, 2006). Evaluation of these drivers and barriers will show that the chances for hydrogen cannot be assessed on the basis of just the merits and flaws of hydrogen and fuel cells, but that a systemic analysis is needed which investigates all pathways and their potential linkages.

### *Local air quality*

Air quality is high on the political and societal agenda in the Netherlands. The European Directive on Air Quality sets strict standards for maximum concentrations of soot, nitrous dioxide and other pollutants. The High Court has issued bans on industrial and residential construction projects because the related traffic intensity will cause too much air pollution. The economic impact amounts to billions of euros, as construction firms cannot do business, municipalities cannot issue land for new projects, and furnishing of new offices, factories and homes is delayed. Using photogenic satellite pictures of air pollution over Europe, environmental and health organizations campaigned for cleaner air to reduce respiratory problems and early deaths, especially among the elderly and the very young.<sup>1</sup>

In fact, all this is going on at a time when air quality is probably better than it was before records were kept. Studies of trends in all sectors consistently show that air quality will improve more in the next decades, to reach levels which the World Health Organization has determined as safe for health. The use of hydrogen as an energy carrier in either fuel cells or internal-combustion engines promises zero or near-zero pollutant emissions, but other technologies can also reduce pollution to the desired levels, and at much lower costs in the near term. Examples are conventional engines with after-treatment, natural gas vehicles and hybrid cars. Hydrogen and fuel cells will be available too late to contribute much to better local air quality, and some ask the question whether the small additional gains from introducing hydrogen are worth the investments. Others argue that the promise of hydrogen is even *delaying* improvements in air quality: good near-term solutions such as natural gas vehicles are not introduced because stakeholders want to avoid investing first in natural gas equipment and then in hydrogen equipment.

### *Climate change*

Emissions of greenhouse gases, especially carbon dioxide, are implicated in climate change. The Dutch target within the EU burden-sharing agree-

ment under the Kyoto Protocol is a 6 per cent reduction in greenhouse gas emissions between 1990 and 2012. According to the government, the Netherlands will meet the Kyoto target with current policies, although environmental NGOs and other critics are doubtful of this. And the post-Kyoto policy is highly uncertain. The main directions will be energy saving, renewable sources, climate-neutral fuels and “clean fossil” (carbon capture and sequestration), but nuclear energy is also back in the discussion.

Hydrogen itself will not inherently reduce greenhouse gas emissions: this depends on the chosen production method. For reasons of production cost and availability of technology, hydrogen is most likely to be produced initially from natural gas through steam methane reforming, then by coal gasification and to some extent from biomass and wind energy.<sup>2</sup> In the long term hydrogen could be produced from all-renewable energy sources, thus reducing CO<sub>2</sub> emissions to virtually zero. But there is doubt about the availability of enough renewables at reasonable cost, and using them for hydrogen production would mean less use of renewables for electricity production. Moreover, central production of hydrogen from fossil fuels with capture and sequestration of carbon dioxide can achieve the same effect, although opportunities are not yet developed for decentralized production of hydrogen. And hydrogen can be converted more efficiently than fossil fuels in fuel cells, thus reducing energy consumption.

The use of renewables for hydrogen production evokes discussion about the energy carrier to which renewables can best be converted. Electricity is a well-established option and, on the grounds of CO<sub>2</sub> abatement costs, hydrogen has difficulty competing against “green current”, especially for power supply in the stationary sector. The lack of good electric batteries means that hydrogen has the edge in transportation applications (although the successful market introduction of hybrids and advanced plug-in hybrids channels funds to battery improvement). But hydrogen storage is not yet at the level it should be to please drivers who are used to the performance of petrol and diesel cars. For heating, natural gas is the option to beat, and here hydrogen has to compete against biogas and synthetic natural gas.

### *Security of energy supply*

Concerns over future availability of fossil resources, geopolitical sensitivity and location, energy prices and vulnerability of centralized energy systems to terrorist attacks have grown recently. Energy flows in the Netherlands show the importance of transit trade, the significance of the refinery industry and the importance of natural gas for domestic use (Van

Arkel et al., 2004). The Netherlands' national energy mix has the highest share of natural gas use in the world. It is used mainly for power generation, heating and as industrial feedstock. Coal is the second-largest energy source for electric power. Nuclear energy and renewables (biomass, wind) have small shares in the energy mix. Transportation is almost completely dependent on mineral oil.

The depletion of energy sources is vigorously debated, especially in the "peak oil" controversy. Availability of "cheap oil" could end in between a few years and several decades, which would put the transport sector under extreme stress. Although crises can hopefully be avoided by taking advance action, there is no doubt that alternative sources to mineral oil are abundant. Both natural gas and coal can be converted to liquid fuels for transportation (gas-to-liquid, coal-to-liquid). Natural gas resources worldwide are enough for a century; coal is available for several centuries. Biomass is a growing source of energy and can also be converted to transportation fuels. Nuclear power plants could in theory be in operation "forever" if a system for recycling and reuse of the radioactive materials could be developed. Wind, sun, earth and tides could each provide endless energy.

As stated before, hydrogen in the Netherlands is most likely to be produced initially from natural gas, then from coal and to some extent from biomass and wind energy. This involves basically the same energy sources as those currently used for power and heating, and at first sight a change to hydrogen will improve energy security only in the transport sector. However, an important asset of hydrogen is that, like electricity, it severs the direct link between the energy source and end-use technology, creating system flexibility and thus improving security of energy supply. Hydrogen (again like electricity) enables all sources of energy to be placed on one equal competitive footing, allowing them to compete in all energy and fuel markets. Fuels, domestic heating and industrial power thus become one and the same market for hydrogen energy (European Hydrogen and Fuel Cell Technology Platform, 2006). This especially helps renewable energy sources to enter a more level playing field.

### *Innovation and competitiveness*

An important reason why Europe embraces fuel-cell and hydrogen technology is competitiveness and innovation. Industry is perceived to be under threat from growing global competition, and new areas for economic growth are being sought. Innovation is certainly an important reason for the car industry to get involved with fuel cells. In addition to the promise of zero emissions, employing fuel-cell (and hybrid) technology allows

wholly new vehicle designs and accessories. Cars can be built with fewer mechanical parts and more electronic systems.

In the Netherlands fuel cells and hydrogen are more in the energy domain than in the innovation domain. The national innovation platform headed by the prime minister has selected the clusters of food and flowers, creative industries, water, and high-tech systems and materials. Innovation in energy technologies did not make the shortlist, although high-tech systems could include energy technologies. In relation to hydrogen, the Netherlands has a strong knowledge base in gas technologies, gas handling, chemical production and engineering, logistics and transportation. There are also companies developing fuel cells, reformers, hydrogen storage technologies and micro-CHP systems. Dutch companies hold a number of relevant patents. So far the government is sceptical about these companies' opportunities to capitalize on their knowledge because it generally sees fuel cells and hydrogen as being in the domain of large international companies. It overlooks that there is scope for involvement of innovative small and medium-sized companies, especially in this early phase where the technologies are still highly experimental.

### *Absence of hydrogen infrastructure*

The absence of a hydrogen infrastructure is often mentioned as a barrier to the introduction of hydrogen. This is both a tautology and not quite true. Various heavily industrialized areas have an infrastructure for hydrogen that is used in manufacturing. Moreover, hydrogen can be introduced as an energy carrier using existing infrastructures for natural gas and electricity. The natural gas grid can be used to transport hydrogen and to supply natural gas for on-site reforming to hydrogen. Similarly the electric grid can provide the energy for on-site electrolysis to hydrogen. Using these existing infrastructures for providing hydrogen has the advantage of low upfront investments and avoidance of lengthy planning procedures. On the other hand, these infrastructures have limited capacity to supply hydrogen. On-site reforming at a large filling station, for example, would equal the natural gas consumption for heating and cooking in a town of 20,000 inhabitants. Admixture of hydrogen to natural gas is limited by pipeline materials, operational procedures and end-user specifications.

Creating a new dedicated hydrogen infrastructure is attractive because of the notion of increasing returns. These are caused by several factors. *Coordination effects* or *network externalities* refer to the interrelatedness of the components in a particular system. The utility of the infrastructure increases with standardization of components and number of users. *Economies of scale* arise from the mechanism whereby once there is a

critical mass, every next user of the infrastructure benefits from the provided services at lower costs, and new services can be added relatively easily. *Learning effects* are the result of experience gained by organizations that use the infrastructure to provide services ever more efficiently. And *adaptive expectations* refer to the situation where a certain alternative is perceived as the best and therefore is able to become the best (Gifford, 1996). Another bonus of creating a new infrastructure is that it opens up the market to new energy suppliers which can challenge the established players and thus shake up the whole energy system.

Choices in the development of a hydrogen infrastructure should be made carefully. Infrastructures have multiple equilibriums, which may lead to possible inefficiencies as the optimum for social welfare may not be the same as the optimum for technical efficiency or the optimum for private enterprise. The system may lock in on one of these optima, and it then becomes difficult to change the whole system (*ibid.*). Laying out the infrastructure for supplying energy to fuelling stations may lock out micro-grid developments and using automobiles as distributed power (powering homes with the car's fuel cell, filling up the tank at home).

### *High costs of fuel cells and sustainable hydrogen production*

It is clear that fuel cells are currently much more expensive than internal-combustion engines, and sustainable hydrogen production is considerably more costly than hydrogen from fossil sources, especially natural gas. The cost of the transition to a hydrogen economy would be prohibitive if the transition has to be made with fuel cells and sustainable hydrogen from the start. It is wiser instead to take a step back in order to make several steps forward: experience can be gathered and a market can be developed with more conventional solutions, such as internal-combustion-engine vehicles fuelled with fossil-based hydrogen. The immediate benefits to the environment and security of energy supply are less, but costs are reduced as well as technical risks, and this is crucial for stakeholder involvement. The conventional technologies can pave the way for the more optimal solutions.

Cost projections indicate that fuel cells and sustainable hydrogen production will become more affordable, and possibly cheaper than conventional alternatives. Price reduction of fuel-cell stacks is steep. The Hy-Ways project identifies the future development of fuel-cell-drive system costs as the major uncertain factor, even before crude oil price developments. The main challenge to hydrogen use is to reach a price level for fuel-cell vehicles near the prices of conventional vehicles. In a range of

analysed cases, HyWays concludes that fuel-cell vehicles will reach a competitive cost level.

### *Technological immaturity*

Besides costs, other parameters of hydrogen and fuel-cell technologies need to improve too. Examples are capacity, weight and volume of hydrogen on-board storage, limited vehicle range (currently around 400 km), the lifetime of the fuel cells, power density and lifetime of batteries, among others. Considerable R&D effort is directed at achieving the needed improvements.

The evaluation of these drivers and barriers shows that the chances for hydrogen cannot be assessed on the basis of just the drivers and barriers or just the properties of hydrogen and fuel cells, but that a systemic analysis is needed which investigates hydrogen alongside other potential pathways and their potential linkages. Such an analysis has not yet been carried out for the Netherlands. In this regard, the technology-oriented practice in energy transition thus far may not be helpful. Instead, the analysis should work back from future energy demand in end-use applications: heating, power, materials and transportation. Energy demand projections should then be matched with the potentials for energy savings, energy efficiency and sustainable energy supply for the different end-use applications, including hydrogen. The potentials would be dependent on the established infrastructures and the alternatives to hydrogen, among other systemic factors.

## Transition pathway for hydrogen in the Netherlands

The potential for hydrogen is currently limited in the stationary sector in the Netherlands, where natural gas provides most of the energy for heating and a large share of the energy for power. Hydrogen could be introduced in two ways in the stationary sector: to provide CHP (combined heat and power) or through admixture to natural gas. Natural gas is widely available, and where individual homes and utility buildings are not connected there is still a good chance that heat and power are provided by natural-gas-fired CHP plants. Almost all homes and utility buildings are connected to the national electricity grid. Introducing hydrogen fuel-cell CHP in the existing built environment therefore means disinvestments, but it can be an option in newly constructed areas. It then has to compete with innovations like direct natural gas fuel cells and Stirling engines.

The other option, admixture of hydrogen to natural gas, seems like wasting a high-grade product which preferably should be used in highly efficient fuel cells. When admixed, the hydrogen can only be used in less efficient combustion engines. On the other hand the natural gas grid is a cheap transport medium, and admixture of climate-neutral gas (hydrogen produced by carbon sequestration, biogas or synthetic natural gas) is one of the few options to “green gas”. Government policy is going in the direction of promoting green gas to consumers, possibly with financial stimuli or producer obligations. There are substantial technical and physical limitations to admixture of hydrogen.

By contrast, the opportunities for hydrogen and fuel cells are tremendous in the transportation sector for several reasons. The move to hydrogen and fuel cells is mainly motivated by the car industry’s desire to be able to supply an environmentally friendly product with equal performance to current vehicles, or preferably better, and for which the energy carrier of choice is always sufficiently available. The fuel cell solves the problem of limited energy storage capacity of electric batteries. Hydrogen can be produced in many different ways, whereas natural gas is not available everywhere and the biofuel potential is limited by the land area and competition from other biomass applications. The absence of local emissions and noise, the technology and the idea of becoming independent of oil create a strong appeal among consumers. As mentioned above, the Netherlands is highly dependent on oil in transport.

In the Netherlands the introduction of natural gas vehicles as an answer to air quality issues in urban areas paves the way for application of biogas, a CO<sub>2</sub>-neutral solution that is already available today. Natural or biogas for transportation will remain a niche application, but the experience gained with high-pressure gaseous fuels will speed up the transition to hydrogen. Similarly the use of liquefied natural gas (LNG) is an important stepping-stone to liquid hydrogen, especially in terms of public acceptance and developing new fuelling and storage technology. Moreover, the hydrogen can be produced centrally or on site from natural or biogas. Hydrogen – pure or mixed with natural gas – can also be used in existing gas-combustion engines, preferably in hybrid vehicles, until fuel cells are ready for the market.

The industrial hydrogen pipeline in the Rotterdam area offers an ideal test ground for demonstration projects with vehicles and fuelling stations, followed by market introduction. Such experiments would provide insight into barriers with respect to licences, safety and technical issues. The Netherlands does not have a strong automotive industry, but by hosting experiments the country can attract knowledge and economic activities related to hydrogen and fuel cells, and thus achieve a good posi-

tion for business. The already strong Dutch knowledge base on gas, import of energy carriers and logistics can be improved more with hydrogen. Such chances may be missed if the Netherlands connects too late to projects like the Hydrogen Highway being developed in Germany, whereas stepping in now may generate added value at relatively low cost (E4tech, 2005).

Fuelling stations in the Randstad (the country's most densely populated area) could be supplied initially by liquid hydrogen in trucks until demand at the stations justifies investments in a pipeline infrastructure. The alternative is on-site hydrogen production, which will stay attractive in areas outside the Randstad where demand may not justify building pipelines. Mass production of hydrogen fuel-cell vehicles is expected around 2015–2020. Hydrogen will initially be produced mainly from fossil sources, with carbon sequestration added on when and if it becomes technically and commercially feasible. The share of hydrogen from renewable sources (wind, biomass) will gradually increase. Once a pipeline infrastructure exists and fuel cells achieve economies of scale, the market chances for fuel-cell CHP also increase.

## Conclusion

To realize a sustainable energy economy requires a new way of thinking and acting, drawing together competencies from various disciplines. The Netherlands has initiated the process of energy transition, in which the government actively seeks public-private cooperation to establish a shared vision and strategy and start joint experiments to investigate promising options. The approach takes into account changes that are not only necessary but also create opportunities for innovation and economic growth. Public-private energy transition platforms have identified the most promising transition pathways. Hydrogen and fuel cells are considered as one potential option in the transition portfolio. For the time being all portfolio options will be pursued. How competition between pathways for feedstock, production capacity, infrastructures and clients can be avoided, or by contrast employed as a selection mechanism, and how optimal synergies between pathways may be achieved merit thought. The role of hydrogen and fuel cells in the portfolio has not been established. The argument in this chapter is that hydrogen has good potential in the transportation sector but much less so in the stationary sector when the technology is considered from a systemic perspective looking at the various pathways in energy transitions and the particular opportunities and costs in the Netherlands.

## Notes

1. Noise pollution is a less debated issue. Fuel-cell vehicles will have an important impact on traffic noise.
2. For a more extensive discussion of hydrogen production technologies see chapters 3, 4, 7 and 17 in this volume.

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## Future prospects and public policy implications for hydrogen and fuel-cell technologies in Canada

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*Kevin Fitzgibbons*

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### Introduction

The development, diffusion and widespread adoption of hydrogen-powered fuel cells in both developed and developing economies have the potential for significant industrial, health and environmental benefits in terms of the emergence of a new, environmentally sustainable, knowledge-based industry, less dependence on fossil fuels and decreased air pollution and greenhouse gas emissions. However, the commercial introduction of this technology into mainstream transportation, stationary power and small-appliance applications faces considerable technical, economic and infrastructural challenges that require public policy responses at the local, regional, national and international levels.

Canada has been actively involved in the development of fuel-cell technologies since the early 1980s. By the late 1990s Canada had achieved a world-leading position in fuel-cell and hydrogen technologies, based in large part on advances in proton-exchange-membrane fuel-cell (PEMFC) technology by Ballard Power Systems and a number of smaller, highly innovative firms. Today there are an estimated 80 Canadian-based firms active in the sector. Ballard (Burnaby, British Columbia) and Hydrogenics (Mississauga, Ontario) are the two largest fuel-cell and hydrogen companies in Canada.

This chapter provides an overview of Canada's current positioning and future prospects in this emerging industry, with a particular focus on the

transportation sector as well as on the range of policy and programme support instruments in place to ensure the future viability of the industry and the successful integration of the technology into the Canadian energy system.

## Overview of Canadian fuel-cell innovation system

### *History*

Canada entered fuel-cell technologies development in the early 1980s, driven by the National Research Council's (NRC) Hydrogen and Energy Storage Program and strong linkages to the University of Toronto. After the NRC programme was shut down in 1985, federal fuel-cell and hydrogen technology development support was taken up by the Ministry of Energy, Mines and Resources.<sup>1</sup>

A key milestone in the development of fuel cells in Canada was a procurement contract issued to Ballard Power Systems by the Department of Defence in 1983 for a small PEMFC stack (Koppel, 1989). The remarkable technical achievements by Ballard in PEMFC-stack power density over the course of the following 10 years not only established Ballard as a leading player in this field, but also ignited a renewed interest in pursuing the technology internationally. In 1998 Ballard received the first major fuel-cell bus demonstration contract by the Chicago Transit Authority. In 1999 it signed strategic alliances with DaimlerChrysler and Ford for fuel-cell automotive engine development, building on an alliance signed with Daimler-Benz earlier in the decade. By 2000, driven in part by Ballard's moves, virtually every major car manufacturer in the world had developed a technical alliance with a fuel-cell producer or established its own in-house development programme.

Other companies also emerged during this period, most notably Stuart Energy Systems (Mississauga, Ontario), an already established hydrogen energy station manufacturer, and Hydrogenics (Mississauga), initially specializing in hydrogen testing and refuelling equipment.<sup>2</sup> Calgary-based Global ThermoElectric entered into the solid oxide fuel cell (SOFC) stationary power market in the late 1990s.<sup>3</sup> Other supply firms such as Dynetek (hydrogen storage) and QuestAir (hydrogen purification) became important players in the Canadian fuel-cell and hydrogen industry. Several firms in the Vancouver area, such as Palteck, Angstrom Technologies, Cellex and Westport, make up an important emergent segment of this industry.

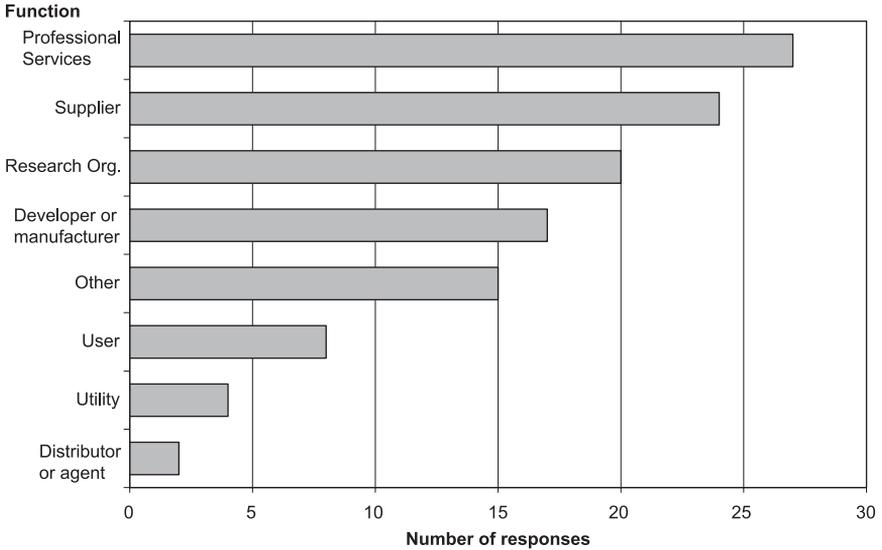


Figure 14.1 Fuel-cell and hydrogen sector in Canada by function  
*Source:* Canada, Fuel Cells Canada and PriceWaterhouseCoopers (2005).

## Canadian fuel-cell and hydrogen industry

In 2004 there were an estimated 125 organizations involved in the fuel-cell sector in Canada, including professional service providers, suppliers and research organizations (fig. 14.1). Seventeen companies are fuel-cell producers and/or systems integrators. Of that total, 51 per cent have been active in the sector for less than five years (Canada, Fuel Cells Canada and PriceWaterhouseCoopers, 2005).

The Canadian industry recorded \$133 million in sales in 2004, down 29 per cent from the previous year, while R&D expenditures were estimated to be \$237 million, a decrease of 18 per cent from 2003 (fig. 14.2).

The technology focus of the Canadian industry mirrors that of the global sector, in that over half of the sector is focused on PEMFCs, and to a lesser extent SOFCs. The Canadian industry's primary market focus is concentrated on stationary applications, as is the case in other jurisdictions, but it differs from the international trends in that there is a greater interest in fuelling infrastructure in Canada (25 per cent) than the international average (14 per cent), and in mobile applications (30 per cent in Canada compared to 14 per cent internationally). The 2005 survey reported a significant (150 per cent) increase in participation by Canadian organizations in demonstration projects from 2002 to 2004 (*ibid.*). Of

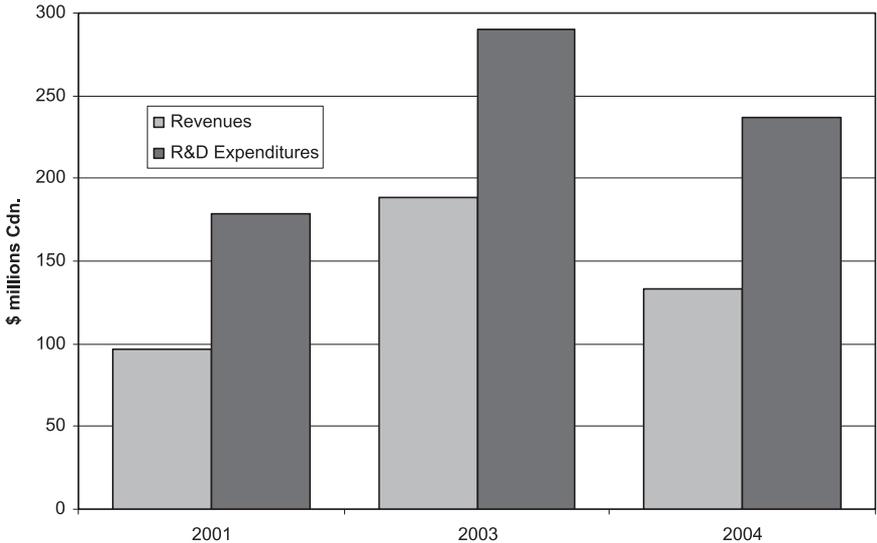


Figure 14.2 Canadian fuel-cell and hydrogen revenues and R&D expenditures  
*Source:* Canada, Fuel Cells Canada and PriceWaterhouseCoopers (2005).

some 215 projects around the world, 59 per cent were inside Canada (fig. 14.3).

The Canadian fuel-cell and hydrogen sectors are supported by two industry associations.

- Hydrogen and Fuel Cells Canada ([www.h2fuelcellscanada.ca](http://www.h2fuelcellscanada.ca)), based in Vancouver, BC, was originally established in 2001 to promote the Canadian fuel-cell industry domestically and internationally as well as facilitating demonstration projects for testing and pre-commercial development. In 2006 it broadened its scope to include hydrogen as part of its mandate.
- The Canadian Hydrogen Association ([www.h2.ca](http://www.h2.ca)), based in Toronto with offices in Montreal, Ottawa and Trois-Rivières, is a non-profit, membership-driven association composed of universities, research organizations, industry and small businesses with the objective of promoting the use and development of hydrogen energy, energy systems and technologies for the purpose of improving the environment.

## Federal support programmes

The Canadian government has a wide array of policy and programme instruments that are either directly or indirectly targeted at promoting the

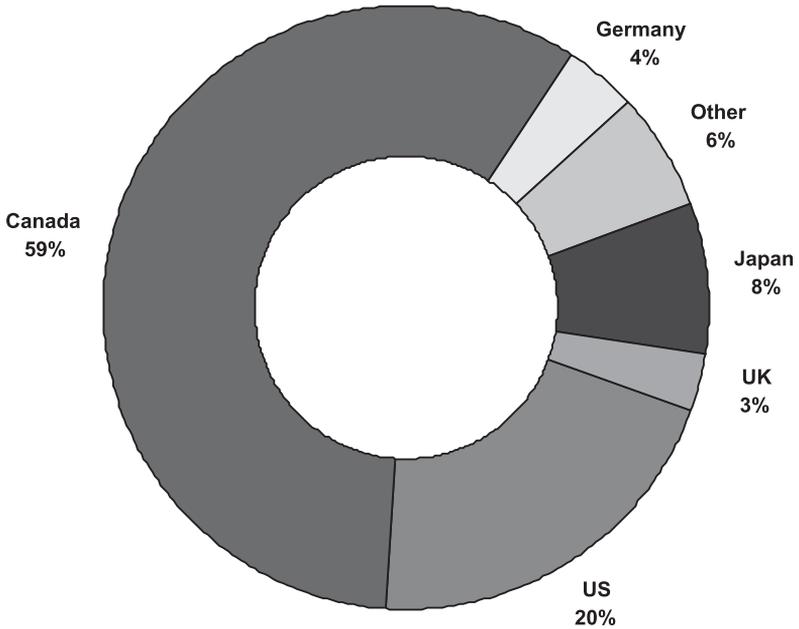


Figure 14.3 Location of demonstration projects, 2004

Source: Canada, Fuel Cells Canada and PriceWaterhouseCoopers (2005).

emergence and global market penetration of Canadian fuel-cell and hydrogen technologies. These measures cover the spectrum from basic and applied R&D to market development support, risk financing, standards development and market demonstration projects.

### *Policy*

Policy support for fuel-cell and hydrogen technology cuts across the mandates of several ministries. The Ministries for Natural Resources and the Environment provide direction for energy, environment and sustainable development policy in Canada. The Ministry of Industry is the government's lead ministry for industrial and science and technology policy. Hydrogen and fuel cells have potential policy implications for virtually every ministry under federal jurisdiction, including transportation, aboriginal affairs, international trade, defence and health and safety.

Policy and programme coordination is facilitated within the federal government by the Hydrogen and Fuel Cells Committee, co-chaired by Industry Canada and Natural Resources Canada (NRCan), with a man-

date to develop, implement and maintain a long-term national strategy for the development of fuel-cell technology and the transition to a hydrogen economy.

### *Key institutions*

NRCan's Alternative and Future Transportation Fuels Program supports the use, development and production of alternative transportation fuels such as ethanol, natural gas and hydrogen fuel cells. It also provides public education, economic and market analyses, research on standards and harmonization of policies. NRCan has a number of programmes in support of fuel-cell and hydrogen technologies, including:

- Canadian Transportation Fuel Cell Alliance (CTFCA)
- CANMET Materials Technology Laboratory
- Hydrogen and Fuel Cell R&D Program
- Industry Energy Research and Development (IERD)
- Process and Environmental Catalyst Program.

Technology Early Action Measures (TEAM) is a federal technology investment programme, co-managed by NRCan, Environment Canada and Industry Canada, created under the Climate Change Action Plan. TEAM supports projects that are designed to develop technologies that mitigate greenhouse gas (GHG) emissions nationally and internationally, and that sustain economic and social development. The programme focuses on projects at the demonstration phase of the commercialization process, where funding and technical assistance are scarce when preparing to bring a new technology to market.

Industry Canada's Energy and Environment Industries Branch is presently engaged in a number of activities related to the development and commercialization of hydrogen and fuel-cell technologies. These activities include increasing access to investment capital and promoting international strategic partnerships, addressing technical barriers to distributed generation and facilitating commercialization roadmaps.

Industry Canada was also responsible for the delivery of Technology Partnerships Canada (TPC), which provided loan support for high-risk, pre-commercialization research for product and process development. In 2003 TPC created the Hydrogen Early Adopters Program, with \$50 million over five years to support up to 50 per cent of eligible costs of hydrogen and fuel-cell projects. Later investments included approximately \$9 million each to both Cellex and General Hydrogen for R&D activities focused on commercialization of fuel-cell forklift trucks. In 2004–2005 \$13.3 million was awarded to four projects involving 32 Canadian organizations.<sup>4</sup>

Regional development programmes are delivered through four federal regional development agencies (Western Economic Diversification, Federal Northern Economic Development, Canada Economic Development for Québec and Atlantic Canada Opportunities Agency).

As the government's primary R&D performer and industrial research support agency, the National Research Council (NRC) identified fuel-cell and hydrogen technologies as a strategic priority in 2001 with the launching of the Fuel Cell Technologies Program and the establishment of the NRC Institute for Fuel Cell Innovation (NRC-IFCI) in 2002 in Vancouver, BC. The NRC's Institute for Chemical Process and Environmental Technologies has also been heavily involved in fuel-cell R&D for several years. In addition to R&D collaborations with industry, the NRC's Industrial Research Assistance Program (NRC-IRAP) provides R&D funding and technical assistance to small and medium-sized enterprises.

The Natural Sciences and Engineering Research Council (NSERC) provides direct research funding to Canadian universities in basic and applied R&D. In 2003–2004 the NSERC invested \$1.4 million in hydrogen-related research and \$3.6 million in fuel-cell research, for a total of \$5 million across all NSERC programmes. The NSERC currently funds five industrial research chairs in hydrogen and fuel-cell technologies.<sup>5</sup>

The Network of Centres of Excellence (NCE) Auto21 Program was formed to focus Canadian research expertise on the task of improving and enhancing the global competitiveness of the Canadian automotive industry. The network currently supports over 230 top researchers working at 37 academic institutions, government research facilities and private sector research labs across Canada and around the world. Auto21's Powertrains, Fuels and Emissions Research Program currently funds four projects focused on automotive applications:

- chemical hydrogen storage process development
- PEM fuel cells and related technologies
- hydrogen safety and infrastructure study for hydrogen vehicles
- on-board fuel-cell-powered auxiliary power units.

Under its Societal Issues Program, Auto21 also funds the Automotive Industry-Government Relations in the 21st Century Program, which looks into the public policy implications of Canada's ability to participate in a hydrogen-based economy.

Sustainable Development Technology Canada (SDTC) was created in 2001 as an arm's-length funding organization to foster the rapid development, demonstration and pre-commercialization of technological solutions that address climate change and improve air quality. Funding is dependent on the formation of sound partnerships involving the key elements of the innovation chain – including private sector, academic,

government and not-for-profit organizations. Examples of recent SDTC-funded projects include:

- Cellex Power Products (fuel-cell-based power products for industrial vehicles)
- Sacré-Davey Innovations (hydrogen fuel refining, storage, distribution and infrastructure)
- Hydrogenics (fuel-cell-powered forklifts).

In May 2007 the federal government committed \$1.5 billion in funding to the creation of the Canada EcoTrust for Clean Air and Climate Change, to provide support to provinces and territories identifying major projects that will result in real reductions in GHG emissions and air pollutants. Cited examples of applications include support for the Hydrogen Highway network of hydrogen fuelling stations for fuel-cell buses and vehicles.

### *Provincial strategies and programmes*

Over the past decade, provinces across Canada have focused on fuel-cell and hydrogen technologies to varying degrees.

Québec has focused primarily on the hydrogen sector because of its considerable hydroelectric resource capacity and the potential synergies with the growing natural gas sector in the province. Centres of expertise, especially at the University du Québec à Trois-Rivières, INRS Énergie and Hydro-Québec, have become the primary platforms for hydrogen technology R&D and demonstration in the province.

The government of British Columbia has been particularly proactive in developing a hydrogen and fuel-cell strategy. With the largest single concentration of fuel-cell producers, system and component suppliers and research institutions, and as the headquarters of Ballard Power Systems, the BC lower mainland is one of the most developed fuel-cell clusters in the world. In 2003 the BC Premier's Technology Council released a four-part industrial strategy for the province in hydrogen and fuel-cell technology.

The vision driving the strategy is to have the world's pre-eminent hydrogen economy by the year 2020. The centrepiece of the strategy is the Hydrogen Highway project for the 2010 Winter Olympics, to be held in Whistler, BC. This event will be an international showcase for the demonstration of a viable integrated multimodal hydrogen system linking Vancouver airport to Whistler. In August 2007 BC Transit awarded a \$46.4 million contract to build the first fleet of hydrogen fuel-cell buses. New Flyer Industries of Winnipeg will manufacture 20 buses, which will be ready for the 2010 Olympics. The buses will have a range of 500 km, a

top speed of 90 km/hr and a life expectancy of 20 years. The three main subcontractors are ISE Corporation (San Diego), which is responsible for the hybrid drive system, Ballard Power Systems, responsible for the fuel-cell modules, and Dynatek Industries of Calgary, which will develop the hydrogen storage system.

In Ontario the provincial government launched a clean energy strategy and a hydrogen and fuel-cell demonstration programme (\$3 million annually for five years).<sup>6</sup>

## Issues for Canadian fuel-cell development

The future prospects for the emergence of a viable and competitive fuel-cell industry in Canada are similar to those of other science-based industries such as biotechnology, nanotechnology and advanced materials. While each industry has issues specific to its own sector, they share similar obstacles in terms of high levels of technological and scientific uncertainty, long gestation periods for commercial development, difficulties in securing appropriate risk financing, lack of established markets and complex regulatory issues. Firms in these industries are small, undercapitalized start-ups with high levels of R&D expenditures and limited, if any, revenue streams.

The most significant barrier facing the fuel-cell sector's market penetration remains the considerable cost disadvantage of fuel cells and hydrogen storage and distribution against established alternatives in the market. In the case of transportation markets, the gasoline-powered internal-combustion engine has a cost-per-unit advantage several orders of magnitude above fuel-cell technologies. Passenger cars typically cost \$30/kW, while PEMFC prototypes are estimated by the US Department of Energy (DOE) to be 100 times more expensive at current low-volume production levels.

Cost issues can be broken down in terms of materials, hydrogen transport, storage and compression, and volume manufacturing. To be viable, fuel-cell power-source production in autos must reach levels of millions of units per year in hyper-competitive global markets where profit margins are razor thin. Most analysts predict that the fuel-cell industry is decades away from competing head to head with consumer auto manufacturers.

Technical issues associated with fuel-cell development are related to materials use, engineering and functionality, durability, engine performance and hydrogen storage and compression.

As an example of company strategies in addressing these issues, the Ballard Power Systems (2003) technology roadmap outlines the technol-

ogy development results and performance targets for 2010 in four areas considered to be of critical importance for commercializing PEMFCs in the automotive market.

- Durability: 5,000 hours.
- Freeze start: under 30 seconds at  $-30^{\circ}\text{C}$ .
- Power density: 2,500  $\text{W}_{\text{net}}/\text{l}$ .
- Cost: \$30/kW (500,000 units/year).

Progress against these benchmarks over the coming five years will be of critical importance to the company's prospects of commercializing its fuel-cell technology in the automotive sector and reassuring its investors of the technical and economic viability of the technology.

Hydrogen technical challenges are primarily focused around transport, storage and compression. Because hydrogen is a light, diffuse gas it is difficult to store on board to give adequate range between fuelling. Large-scale storage and transportation requires over 21 times the storage capacity of conventional gasoline (DALCOR Consultants, 2004). Calgary-based Dynetek Industries is one of the world's leading developers and suppliers of advanced lightweight composite pressure vessels. Research into solid-state hydrogen storage solutions based on metal or chemical hydrides and carbon nanotubes is one area being actively pursued by a number of Canadian universities.

If PEMFCs are to be successful in the automotive market, hydrogen purity will be a critical performance factor. Carbon monoxide traces of fewer than 10 parts per million can poison existing PEMFC catalysts. Purification technologies such as pressure swing adsorption, developed by Vancouver-based QuestAir, will be important to the future commercialization of the technology.

Hydrogen infrastructure access, availability and safety will be a fundamental condition for the growth of fuel-cell applications in transportation markets. Canada is the largest per capita producer and user of hydrogen in the OECD at about 2.88 million tonnes per year, of which over 90 per cent is produced in western Canada. Should fuel cells be successful in penetrating the automotive and transport sectors in the coming decade, the rate of growth for hydrogen demand would increase exponentially.

There are currently five large-scale compressed-hydrogen storage facilities in Canada, situated near production sites. There are a limited number of fuelling stations located in testing and demonstration sites in Vancouver, Victoria, Toronto, Ottawa, Trois-Rivières and Prince Edward Island.

Most marketing studies point to small stationary power applications and appliances as short-term market opportunities. In the medium term, the most promising niche applications in the transportation sector include

Table 14.1 Fuel-cell and hydrogen demand projections, 2023

Market/scenario	Status quo	Low-carbon agenda	Hydrogen priority
<i>Number of vehicles</i>			
Passenger	46,591	126,818	338,660
Fleet	2,303	4,218	17,436
Transit	164	433	1,260
<i>Hydrogen (tonnes/y)</i>			
Passenger	11,650	31,700	77,165
Fleet	5,760	10,545	43,590
Transit	2,990	8,085	22,995

specialized industrial equipment, forklift trucks, mining vehicles, urban bus fleets and car fleets.

Estimates based on three government policy scenarios developed by DALCOR Consultants (*ibid.*) see market penetration in the passenger, fleet and urban transit markets ranging considerably between 2015 and 2023 (table 14.1).

Until 2007 Ballard remained primarily focused on automotive applications as its core market strategy. Alliances with Ford and Daimler-Chrysler have provided access to key marketing and manufacturing capabilities. Other firms such as Palcan, Hydrogenics and Cellex are targeting niche markets for small (<25 kW) applications, such as scooters, pleasure-craft and forklifts.

Access to risk capital was identified by the fuel-cell industry as a major impediment to commercialization. According to the Fuel Cell and Hydrogen Industry Survey (Canada, Fuel Cells Canada and PriceWaterhouseCoopers, 2006), expected domestic financing by source of funding is \$1.2 billion from 2006 to 2011 in the Canadian fuel-cell sector, of which 8 per cent will be from private equity. Canadian and foreign government funding represents 29 per cent of all capital financing for the industry, and public capital markets have grown to 49 per cent from only 16 per cent in 2003.

The BC fuel-cell sector has raised \$239.7 million in venture capital over the past four years. Large institutional investors in Canada have traditionally had much lower exposure to high-tech start-ups than their counterparts in the United States. In Canada technology ventures represent less than 2 per cent of pension-fund holdings, while in the United States pension-fund technology-venture investment represents 11 per cent of institutional portfolio holdings (Industry Canada, 2003). Long gestation periods and lack of adequate financing instruments for fuel-cell

companies can severely handicap start-up firms that face huge development and marketing costs.

Policy and government support for risk financing in high-technology industries is primarily driven through the tax system, where annual credits from the Scientific Research and Experimental Development (SR&ED) programme are estimated at over \$1.2 billion. However, SR&ED tax credits are focused on R&D and are redeemable against revenues, which creates severe cash-flow problems for many early-stage firms in the industry with limited or non-existent revenue streams.

Other risk-financing instruments for Canadian firms include the Business Development Bank seed and venture capital investments that focus on higher-risk technology ventures. Programmes such as TEAM, the SDTC, TPC and the NRC-IRAP provide varying levels of risk financing in the form of grants or repayable loans.

## Future prospects and outlook

A key development in Canada and internationally in recent years has been a shift from small bench and laboratory demonstration projects to larger integrated hydrogen system projects. These demonstration projects provide the basis for testing and evaluating fuel-cell and hydrogen technologies in an integrated, interactive system that includes transport and stationary applications with hydrogen transport, storage and refuelling platforms. These projects also create more high-profile exposure and general public awareness.

### *Demonstration and systems integration projects*

#### *Hydrogen Highway – Olympics 2010*

The Hydrogen Highway is a coordinated, large-scale demonstration and deployment programme intended to accelerate the commercialization of hydrogen and fuel-cell technologies. It consists of seven nodes – each with plans for its own sustainable microcosm with hydrogen fuelling infrastructure as well as a range of transportation and stationary applications (fig. 14.4).

By creating an early-adopter community of technology developers and users throughout British Columbia, the Hydrogen Highway will play an integral role in removing barriers for hydrogen and fuel-cell commercialization. The project will develop a critical mass of expertise, knowledge and experience in the area, provide data for developing international codes and standards around implementing the technology, stimulate demand for the technology by allowing the media and general public to



Figure 14.4 The Hydrogen Highway project

feel, touch and see the benefits of a hydrogen economy, open doors for international partnerships and create a hydrogen infrastructure legacy in Canada.

The original partners for the development of the Hydrogen Highway are the Methanex Corporation, BC Hydro and the NRC-IFCI. With the July 2003 announcement that Whistler would host the 2010 Winter Olympics, the project has the opportunity to demonstrate the viability of a hydrogen economy system on a high-profile international stage. Since then, Industry Canada and NRCan have committed substantial funding towards fuel-cell and hydrogen research and demonstration projects. The province of British Columbia has become a champion of the Hydrogen Highway, viewing it as the backbone of the BC hydrogen and fuel-cell strategy document. Examples of Hydrogen Highway projects include:

- a hydrogen fuelling station and storage tower that will power several Ford Focus fuel-cell vehicles
- photovoltaic panels producing solar energy to power an electrolyser and generate hydrogen at the NRC-IFCI
- a solid oxide fuel cell to provide heat and power to the NRC-IFCI
- hydrogen-fuelled internal-combustion-engine vehicles, hydrogen-enriched natural-gas-powered vehicles and hydrogen-powered generators at UBC
- sustainable residential community feasibility studies and development in the surrounding area at the University of British Columbia.<sup>7</sup>

### *Hydrogen Village*

The University of Toronto Mississauga's (UTM) Centre for Emerging Energy Technologies, Hydrogenics and the city of Toronto authored a framework document for the Hydrogen Village (H2V) concept in the Greater Toronto area. Now with close to 40 members, the partnership is a pioneering collaboration of industry, government and academia that is determined to accelerate the commercialization of hydrogen and fuel-cell technology in Canada.<sup>8</sup>

Federal granting programmes that provide financial support for the development of fuel-cell and hydrogen technologies are already encouraging prospective applicants to pass their project proposals through the H2V for review, comment and endorsement. The UTM's Centre for Emerging Energy Technologies has three projects in this partnership currently under federal review:

- townhouse retrofit for fuel cells (partners: Fuel Cells Technologies and Air Liquide Canada)
- fuel-cell emergency power supply
- hydrogen (ICE)/battery hybrid bus (partners: UTM, Stuart Energy, BET Services and the city of Mississauga).

### *Hydrogen Corridor*

The Québec-Ontario Hydrogen Cooperative is planned as a bi-provincial network of innovative communities that traverses Canada's industrial heartland.

The mission of the Hydrogen Corridor Cooperative is to accelerate the integration of a sustainable hydrogen economy through the synergy of hydrogen and fuel-cell community initiatives within the region. The cooperative will essentially be realizing the hydrogen age. It will be a concentration of interconnected municipalities, companies, specialized suppliers, service providers, firms in related industries and associated institutions (universities, standards organizations and trade associations), linked by commonalities and complementarities that cooperate in the hydrogen

and fuel-cell sector to facilitate the deployment of the hydrogen economy. It will also serve as a focal point for public outreach and awareness and will be a driver for broad market acceptance of hydrogen and fuel-cell products in the region. It is designed to be a sustainable collaboration of communities for the introduction of GHG-reducing technologies, strengthening Canadian hydrogen and fuel-cell energy technology companies and creating new ones.

### *Large fleet demonstration and early adoption programmes*

From the perspective of transportation applications and introduction to the automotive markets, the federal government is concentrating on large fleet applications, and in particular urban transit applications where early-stage economies of scale can facilitate investments in hydrogen infrastructure and fuel-cell technology platforms.

In January 2005 the Canadian Transportation Fuel Alliance released a major study (Natural Resources Canada and BC Transit Authority, 2005) on socio-economic viability and policy issues with respect to the integration of hydrogen-powered fuel-cell technologies in Canadian urban transit systems (UTSs). Canadian urban transit bus fleets are currently powered almost exclusively by diesel, and are a natural early adopter of hydrogen fuel-cell technology. The study points to key factors and benefits to adoption in this sector and provides 50 recommendations to the UTS industry, bus manufacturers, fuel-cell system suppliers, hydrogen storage system suppliers, hydrogen fuel and fuelling system providers, training institutions and governments. Canadian UTSs are an ideal sector to engage because:

- there are over 2.42 billion riders per year
- the number of vehicles – approximately 12,000 – is a sizeable market
- UTSs consume over 360 million litres of diesel and 17 million m<sup>3</sup> of natural gas per year
- the transit application is visible to the public
- transit properties have a centralized infrastructure that can be adapted to hydrogen
- urban transit applications have global market relevance.

### Summary

Canada's current and potential future positioning as a key player in the development and commercial application of fuel-cell and hydrogen technologies form an important case study for Canadian S&T policy because of a number of factors.

- It is an emerging technology with applications in a number of industries.
- It is at the interface among a wide range of public policy issues, including environmental sustainability, climate change, energy use and conservation, transportation planning, industrial development, science, technology and innovation and regional development.
- It is an industrial issue where major market segments in automotive, stationary and portable power could represent billions in exports and energy savings.
- It is a sector where close policy coordination at the municipal, provincial, federal and international levels will be of critical importance to the future success of the industry and technology.

However, with the January 2006 federal election and the arrival of the Conservative Party in power, the prospects of a national strategy in hydrogen and fuels cells have diminished. The strategy document developed in 2005 was not approved by the Liberal government before the federal election, and the focus of the new Conservative government's climate change policy has subsequently been more on supporting the development of biofuels in Canada. Nevertheless, the Canadian experience serves as an important case study more generally for other countries in understanding the problem of developing policy for a disruptive technology.

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The views expressed in this chapter are those of the author and do not necessarily represent the official position of the Government of Canada or the Office of the National Science Advisor.

## Notes

1. Now Natural Resources Canada (NRCan). The NRC re-entered the field in 2001 with the establishment of a fuel-cell R&D programme, and then the creation of the Institute for Fuel Cell Innovation in Vancouver in 2002.

2. In February 2005 Stuart Energy Systems was acquired by Hydrogenics.
3. Global Thermoelectric was sold to Versa Power, a US-based firm, in 2004.
4. The terms and conditions for Technology Partnerships Canada expired on 31 December 2006 and the programme no longer exists.
5. For a listing of the industrial research chairs see [www.nserc.gc.ca/partners/chairs\\_e.asp](http://www.nserc.gc.ca/partners/chairs_e.asp).
6. See [www.ontariocanada.com](http://www.ontariocanada.com).
7. See [www.nrc-cnrc.gc.ca/highlights/2004/0405hydrogen\\_e.html](http://www.nrc-cnrc.gc.ca/highlights/2004/0405hydrogen_e.html).
8. See [www.utm.utoronto.ca/1560.0.html](http://www.utm.utoronto.ca/1560.0.html).

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# 15

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## Hydrogen and fuel-cell activities in China

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### Introduction

The rapid growth in China in recent years has had major consequences for both energy consumption patterns and the environment. Hydrogen and fuel cells represent one solution among a range of options currently being explored to deal with this situation.

This chapter reviews China's policies and practices with regard to research and development on hydrogen and fuel cells and their application in fuel-cell vehicle development. It also provides an overview of the testing and demonstration projects and partnerships that are advancing the underlying technological base and speeding the process of commercializing hydrogen fuel-cell vehicles by 2020.

### The challenges in energy and the environment

Energy consumption in China is now second only to the United States. In 2006 China's total primary energy consumption reached 1,697.8 million tonnes of oil equivalent. Of this, coal accounts for 70 per cent, oil for 20.6 per cent and hydropower for 5.56 per cent. All remaining primary energy sources, such as natural gas, nuclear power and renewables, account for only 3.9 per cent of China's primary energy consumption.

China has abundant coal reserves, but its oil resources are more limited. Rapid industrialization has thus led to heavy reliance on coal as a

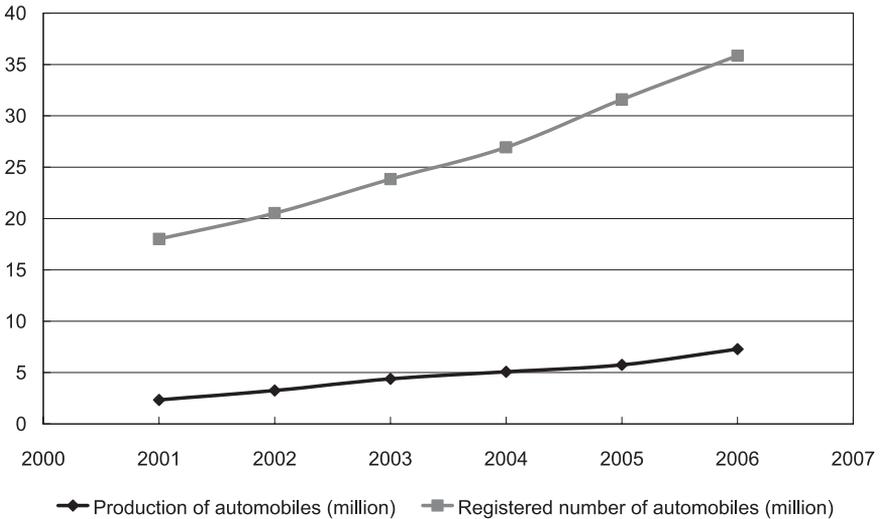


Figure 15.1 Trends in vehicle ownership in China

primary fuel in industry. Seventy-five per cent of the electricity generated in China is produced by coal-fired plants, and the country continues to face a shortage of electricity, especially in the high-growth south.

Rapid growth, rising incomes, decreasing car prices, urbanization and a variety of policies that support the automobile sector as a major industry and employer have contributed to the steep increase in vehicle ownership in China over the past decade (fig. 15.1). If current trends continue, it is expected that the vehicle fleet in China will grow to 10 times its present size by 2020.

A number of challenges result from the growth in demand for energy and the current structure of energy consumption. Although China does have oil reserves and produced some 183 million tonnes of oil in 2006, it imported net 136.2 million tonnes of crude oil and 32.4 million tonnes of oil products, accounting for over 43 per cent of its total oil consumption in 2006. The year before it had overtaken Japan as the world's second-largest petroleum consumer. The projected growth in vehicle ownership over the next 10 years will substantially increase the need for petroleum imports. It is estimated that self-reliance in oil will decline to 50 per cent in 2010 (table 15.1). While the situation is not critical at this point, energy security is likely to become a problem in China in the future and the Chinese government has already begun to take measures to encourage the development of more energy-efficient vehicles.

Attention is also being paid to the level of CO<sub>2</sub> emissions, especially in

Table 15.1 Oil demand, production and imports, 2000, 2005, 2010 (M ton)

	2000	2005	2010
Oil demand	220	265–285	300–340
Self-production	160	170–180	180–200
Net imports	59	85–115	100–160
Self-reliance	73%	63%	50%

urban areas. The high reliance on coal and oil has raised CO<sub>2</sub> emission levels dramatically in recent years. China is now the second-largest contributor of CO<sub>2</sub> after the United States. But China's CO<sub>2</sub> emissions per capita were just 87 per cent of world average per capita and 33 per cent of the OECD average. Rising levels of vehicle emissions as well as emissions from the power sector are important contributors to growing urban pollution in China.

### The policy context

To deal with these problems China has adopted a dual approach in the transport sector. This consists of improving existing systems and introducing alternative fuels, while simultaneously advancing in the development of new technologies. The Chinese government has not attempted to pick “winners” from among alternative technological trajectories, whether in fuels, such as CNG and ethanol, or in vehicles – electric (EVs), hybrids or fuel-cell vehicles (FCVs) – but rather has focused on stimulating rapid movement along the learning curve and towards commercialization in a range of different technologies.

Over time, however, the emphasis in China's policies towards the transport sector has changed. During the Ninth Five-Year Plan (1996–2001), for example, Chinese policies with regard to the introduction of both alternative and new types of fuels and vehicles tended to take a supply-side approach, focusing primarily on research and development activities. While the emphasis on R&D continued through the Tenth Five-Year Plan (2001–2005), the Ministry of Science and Technology (MoST) began to pay greater attention to demonstration and testing projects with a view to downstream commercialization.

Most recently policies aimed at stimulating the demand side, notably the use of hydrogen and other alternative-energy vehicles, have been introduced. On 30 May 1998 China signed the Tokyo Commitment, which was put into effect in February 2005. In the Eleventh Five-Year Plan for economic development (2006–2010), China has announced its intention

to reduce energy consumption per GDP unit by 20 per cent and pollution per GDP unit by 10 per cent. Priority will be given to the development of public transportation in urban areas and to promoting the use of alternative energies such as CNG, LPG and methane gas derived from coal. In 2004 the largest coal-to-liquid (gasoline, diesel, etc.) refinery in the world was built in China. This is being followed by the construction of the world's largest coal-to-olefin (ethylene, propylene, etc.) refinery, which was begun in 2007.

### Promoting alternative-fuel vehicles

Since the late 1990s the Chinese government has encouraged the use of alternative-fuel vehicles (AFVs), notably those using CNG, LPG, methanol and ethanol. In April 1999 a programme to demonstrate clean vehicles was initiated in 12 large cities across the country, including Urumchi, Harbin, Xi'an, Chongqing, Beijing, Shanghai and Shenzhen. By the end of 2001 there were a total of 109,650 AFVs on the road, including 84,673 LPG vehicles and 24,805 CNG vehicles, as well as 368 re-fuelling stations in these 12 cities. Over the next few years the number of CNG and LPG vehicles continued to rise, reaching some 300,000 units at the end of 2005. By 2008 about 4,000 CNG buses and 31 CNG refuelling stations will be operating in Beijing. All buses in Guangzhou already operate on LPG. The ethanol production capability for vehicle applications is currently 1.02 million tonnes and a programme to popularize gasoline with 10 per cent ethanol is being carried out in nine of China's provinces.

Increasingly strict automobile emission standards have been mandated in China since the year 2000. On 1 July 2000 the selling of and refuelling with leaded gasoline was banned across the country. This was followed by the application of a succession of Chinese vehicle emissions standards. In April 2001 Chinese vehicle emission standard GB-18352-1 (equivalent to EU-1) became effective across China. GB-18352-2 (equivalent to EU-2) took effect in Beijing and Shanghai on 1 January 2003 and throughout China two years later. GB-18352-3 (equivalent to EU-3) was applied in Beijing and Shanghai on 1 January 2005 and will probably be in effect across China by 1 January 2010. The EU-4 vehicle emission standard will be effective in Beijing in 2008.

### *Alternative fuels and vehicles*

With regard to existing systems, policies initially focused on improved internal-combustion engines (ICEs), battery EVs, on which research had been under way in China since 1990, and hybrids. During the Ninth Plan

period MoST created an EV demonstration zone in Shantou and funded research on EV standards. Over the following four years MoST's hi-tech programme targeted at EVs, known as the 863 Programme, spent US\$70 million on battery and hybrid EVs.

Then in 2004, to stimulate the process of achieving fuel economies from the demand side, China's State Council approved the country's first automobile fuel-efficiency standards, which required 16 different car and truck weight-based classes to achieve between 19 and 38 miles per gallon (mpg) by 2005, and between 21 and 43 miles per gallon by 2008. As one reporter noted, by 2007 China "had imposed more stringent fuel economy standards than the United States", but not quite as stringent as those adopted by auto makers in the European Union. China had also "raised its consumption tax to as much as 20 percent on gas guzzlers, while cutting it to 1 percent for cars with small, fuel-sipping engines. And Chinese tax authorities are studying whether to introduce tax incentives for buyers of hybrids" (Bradsher, 2007).

The government also introduced new rules governing car financing, along with measures to dampen consumer spending as part of its broader effort to cool an overheating economy.

### *Hydrogen fuel-cell vehicle development in China*

The basis for China's fuel-cell research was laid in the early 1970s as part of its national space mission. At that time the Dalian Institute of Chemical Physics (DICP) successfully developed two types of alkaline fuel-cell (AFC) systems. Research on solid oxide fuel cells (SOFCs) was also undertaken.

But AFCs and SOFCs are mainly used in industry and for stationary power. It is the proton-exchange-membrane fuel cell (PEMFC) that has been the primary focus of fuel-cell research in the transport sector. From the early 1990s, alongside efforts to improve the efficiency of existing systems, China has sought to advance in the development of new hydrogen fuel-cell-based systems for both stationary power and the transport sector. By 1999 a 5 kW PEM fuel cell had been developed and was used by Tsinghua University to power a cart. This was the period in which MoST and the Chinese Academy of Sciences (CAS) began to investigate the integration of fuel cells into vehicles through larger research projects.

The Chinese hydrogen fuel-cell roadmap began to take shape in 1998. Not until the launch of the 863 Programme in 2001, however, was significant funding allocated to research on fuel cells and their integration into FCVs. Between 2000 and 2010 fundamental research and development as well as engineering R&D are being undertaken simultaneously, with a view to producing between three and 10 fuel-cell vehicles during this

period. The phasing-in of up to 100 fuel-cell vehicles in demonstration projects is planned and the target of commercializing some 1,000 fuel-cell buses and other FCVs by 2020 was set. The work on hydrogen fuel-cell systems during this period has also included research on the production of hydrogen from both fossil fuels and renewable energy.

Although the remainder of this chapter will deal with progress in the development of hydrogen and fuel-cell vehicles, it is important to note that China has not abandoned the energy sector more generally. A range of policies is being pursued to deal with the current dependence on coal. The Eleventh Five-Year Plan (2006–2010) and the Medium and Long-term Energy Development Strategy and Plan to 2020, for example, aim to improve the efficiency of the energy sector and bring energy intensity in line with international best practice. This includes increasing natural gas penetration, aggressively developing renewable energy use, especially for power generation, further developing clean coal technologies and securing energy supply to meet the country's growing needs. The plan targets a 20 per cent improvement in energy efficiency and conservation by 2020.

### Moving down the learning curve

China's hydrogen and fuel-cell strategy is directed by MoST, which provides funds for R&D and demonstration projects to national and university research institutes as well as a few hi-tech companies, supported by the National Development and Reform Commission, which provides funds to key companies for construction and industrial projects. In addition it collaborates with the municipal governments of Beijing and Shanghai, which co-funded fuel-cell vehicle technology projects in the period 2002–2005, and with the provincial government in Hubei province, which through its local hi-tech R&D programme collaborated in FCV technology over the period 2005–2007.<sup>1</sup>

Conscious efforts to build domestic research capacity in Chinese universities and firms, to network local enterprises, research institutes and universities and to stimulate learning through the multitude of partnerships that have been established with foreign automobile, fuel-cell and oil companies are at the core of China's capacity-building strategy in the development of hydrogen fuel-cell vehicles.

By 2005 more than 60 Chinese institutions and companies were working on hydrogen and fuel-cell technology. The Chinese Academy of Sciences (CAS), for example, under the key Project Innovation Act, undertook fuel-cell stack technology research from 1996 to 2000 and research on fuel-cell engines and hydrogen technology from 2001 to 2004

at the DICP. Sunrise Power (a joint-stock company owned by the DICP, Shanghai Automotive Industry Company (SAIC) and others) and Shanghai Shen-Li High Tech (a private company) also focus on fuel-cell engine development. Tsinghua University works on the integration of fuel-cell engines into buses for testing and demonstration, and Tongji University and Shanghai Fuel Cell Vehicle Powertrain Company, a joint venture between Tongji University and SAIC, focus on vehicle integration for cars rather than buses. Other organizations involved include the Automotive Electric Institute of Jiaotong University, the China Automotive Technology and Research Centre and Beijing Fuyuan Century Fuel Cell Power. China's largest auto maker, SAIC, is also funding a small amount of internal research on fuel cells and their incorporation into hydrogen fuel-cell cars.<sup>2</sup>

Capacity building has been carried out through three main national projects in which these Chinese institutions have collaborated with each other and with foreign partners.

The largest of the hydrogen and fuel-cell research projects was the five-year 863 Programme. Managed by MoST as part of the Tenth Five-Year Plan, its total budget was approximately US\$110 million. Although the programme focused mainly on battery-powered and hybrid electric vehicles, more than US\$40 million went to research on fuel cells and fuel-cell stacks. The project also provided support for the integration of fuel-cell stacks into vehicles for testing demonstrations.<sup>3</sup>

In addition to its domestic fuel-cell and FCV programme, China also participates in an international cooperation project, Demonstration for Fuel Cell Bus Commercialization in China, co-funded by the Global Environment Facility (GEF), the UN Development Programme (UNDP), MoST and the Beijing and Shanghai municipal governments. The project is designed to catalyse improvements in fuel-cell vehicle performance and a reduction in costs. Through a process of international bidding it is intended to purchase between six and 12 fuel-cell buses and build two hydrogen fuelling stations – one each in Beijing and Shanghai. The fuel-cell buses (FCBs) will operate as public transit vehicles in Beijing and Shanghai and stimulate technology transfer in FCBs and their hydrogen refuelling infrastructure. The total budget is approximately US\$32 million,<sup>4</sup> supported by the Promoting Sustainable Transportation Programme under the GEF Climate Change Programme. DaimlerChrysler won the bidding and supplied three fuel-cell Citaro buses for demonstration in Beijing for two years. Since 25 October 2006 BP, SinoHytec and Tongfang Corporation have cooperated to build the hydrogen fuelling station in Beijing; BP provided technical and in-kind support.

The third was a smaller project, the National Hydrogen Energy Project 973, with a budget of approximately US\$3 million, designed to run from

2000 to 2005. It was aimed at strengthening fundamental R&D, notably with regard to the production, storage and distribution of hydrogen and fuel cells. Much of the research and development under this project took place in Dalian. The project has just been renewed.

Through these projects, China has moved quite rapidly down its learning curve in the power of its fuel-cell stacks, the development of hydrogen fuel-cell cars, the development and deployment of hydrogen fuel-cell buses and the building of hydrogen refuelling stations.

### *Fuel cells and fuel-cell stacks*

Between 1990 and 2007 the power of fuel cells produced in China increased from a 5 kW fuel-cell stack able to power a cart with a maximum speed of 20 km/h to a PEM fuel-cell stack in 2001 that could generate 25 kW, enough to power a light bus or mini-van at over 100 km/h and then to a 60 kW stack that in 2007 powered the Shanghai fuel-cell car capable of operating at a speed of 150 km/h.

China now has more than 400 patents related to fuel cells. These span the full range from catalysts to system integration. PEM fuel-cell research at the DICP has mainly focused on catalysts, membranes, catalyst layers and flow dynamics. Some work is also under way on stack mechanics. In addition to increasing the power of PEM fuel-cell stacks, materials and components used in fuel cells have been streamlined. In developing PEMFCs, the DICP has moved from hand-crafted graphite, embossed expanded graphite and punched metal to moulded composites. Table 15.2 illustrates the progress that has been made reducing platinum loadings and increasing current density in PEM fuel cells over the years 1996–2000.

Research is also currently under way on hydrogen production. It focuses mainly on the costs of on-site and mobile production, natural gas reforming processes, compact size, multifunction catalysts and system integration. China has developed a 75 kW hydrogen methane (MeOH) reformer.

Table 15.2 Progress in platinum loadings and current density, 1995–2002

	Platinum loading	Current density
1995	4–8 mg/cm	400 mA/cm <sup>2</sup>
1996	1–4 mg/cm <sup>2</sup>	400 mA/cm <sup>2</sup>
1998	0.5–1 mg/cm <sup>2</sup>	500 mA/cm <sup>2</sup>
1999	0.02–0.4 mg/cm <sup>2</sup>	600 mA/cm <sup>2</sup>
2000	0.2 mg/cm <sup>2</sup>	1.3 A/cm <sup>2</sup>



Figure 15.2 Chinese fuel-cell cars

### *Fuel-cell cars*

The five-year 863 Programme that began in 2001 was highly successful in building the knowledge base that has led to the development and early commercialization of hydrogen fuel-cell cars (fig. 15.2). Over the course of this programme, three generations of platforms for hydrogen fuel-cell vehicles were developed (table 15.3). These were based on the Volkswagen Santana.

The earliest of these platforms used a large power battery. Subsequently this was reduced and complemented by increasingly powerful hydrogen fuel-cell stacks. In June 2006, at the Michelin Challenge Bibendum in Paris, Shanghai's Start-3 fuel-cell-driven car received four gold medals, "winning class A ... in carbon dioxide emissions, emissions, noise and fuel efficiency" (*People's Daily*, 2006).

The Start team, led by Tongji University, included SAIC, a state-owned Chinese company that grew from its initial base in tractor production to become a diversified automotive group with sales of about 850,000

Table 15.3 Progress in developing fuel-cell cars

Model	Start-1 S2000	Start-2 S3000	Start-3 S3000	Shanghai FC car
Power: FC/battery	30 kW/30 Ah	35 kW/15 Ah	40 kW/15 Ah	50 kW
Traction motor	50 kW	60 kW	65 kW	
Max. speed (km/h)	105.8	115	122	150
Acceleration (0–100 km/h), seconds	36.6	26.7	19	15
Range (km)	231	217	230	300
Fuel efficiency (kgH <sub>2</sub> /100 km)	1.394	1.132	1.12	1.2

Source: Ma (2007).

cars in 2004. SAIC has joint ventures with the German car group Volkswagen and the US car group General Motors.

In 2006 the Start team initiated a new-generation platform, changing the configuration and using improved parts. As in Start 1, 2 and 3, the objective was to develop a single chassis to be shared among several cars. By the end of 2006 they had developed two vehicles: one based on the VW Passat and the second, the Shanghai fuel-cell car, based on a Rover. The latter technology was transferred to SAIC to tool up for production in 2008. The Shanghai fuel-cell car's specifications show a marked improvement over earlier Chinese HFCs (Ma, 2007).

FCV demonstration projects have also been developed for Shanghai. One of these involves 10 fuel-cell passenger cars to operate on the route between Hongquiao Airport and Shanghai. The purpose of this demonstration project is to provide a continuous flow of test information to the fuel-cell and FCV industry, which is clustered in Shanghai. Shanghai will also be involved in phase two of the China-GEF-UNDP hydrogen fuel-cell bus project.

### *Fuel-cell buses*

In contrast to the development of fuel-cell cars, China's fuel-cell bus development has two parts: one is supported by the 863 Programme and involves the development of a hybrid fuel-cell bus in Tsinghua University; the other is the GEF-UNDP project.

By 2005, in the context of the 863 Programme, Tsinghua University had developed three types of hybrid-configuration fuel-cell buses (fig. 15.3). Their test running shows that the hybrid fuel-cell bus had good fuel efficiency (table 15.4).

The GEF-UNDP project's main objectives were to create awareness of frontier hydrogen fuel-cell bus technology around the world through a series of study tours; develop technical, managerial and planning capabilities in China relating to fuel-cell buses; stimulate technology transfer to Chinese research institutions and enterprises through public tenders for fuel-cell buses and hydrogen refuelling infrastructure; determine the current technical, operational and commercial viability of fuel-cell buses; and prepare the terrain for widespread commercialization of fuel-cell buses in China (Lun, 2006). Experts from the National 863 Electric Vehicle Plan were thus involved in the fuel-cell bus demonstration project from the outset.<sup>5</sup>

The UNDP-GEF fuel-cell testing and demonstration project was created with a view to promoting sustainable transport in developing countries. Its focus on the development of public-transit systems, such as bus transportation, and new technologies led to the move towards a hydrogen

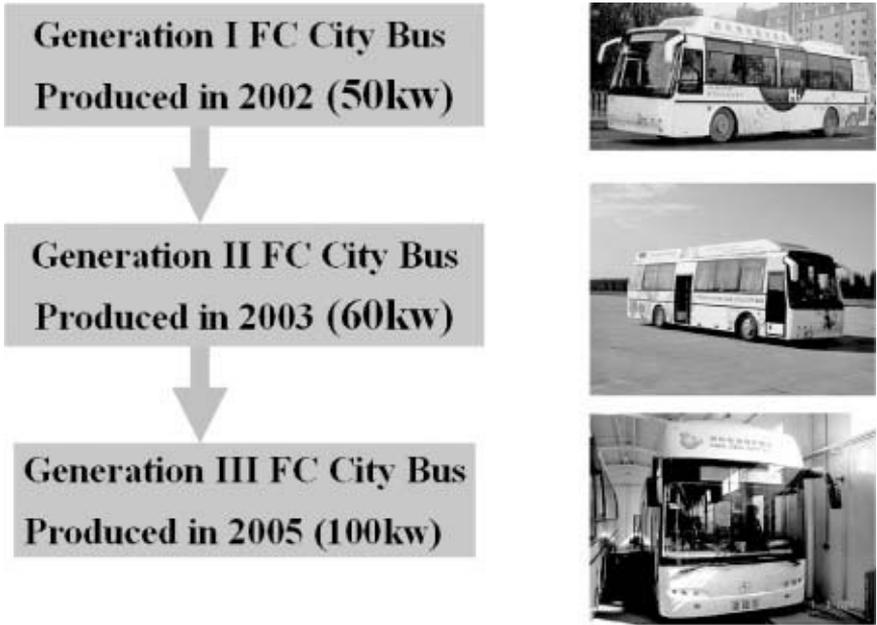


Figure 15.3 Three generations of fuel-cell buses

Table 15.4 Performance data for fuel-cell bus

	Acceleration	Braking	Slalom	Noise	Emissions	Fuel efficiency*
FC bus, Tsinghua University	24.5 s	28.9 m	–	76 dB	0	19.68 L/100 km

Source: Data from Bibendum 2004, Shanghai, China.

\* Gasoline equivalent

fuel-cell bus demonstration project in China. Beijing is the country’s political capital, and government support for the fuel-cell industry and the commercialization of fuel-cell buses in China will be determined here. In terms of its impact as a demonstration project, it was also important to have fuel-cell buses operational before the Beijing Olympics in 2008. Phase one of the project thus focused on Beijing. The supply contract for the first three FCBs was signed with DaimlerChrysler (DCX) in May 2004. The bus hand-over ceremony took place in November 2005, and by May 2006 a FCB maintenance facility staffed by an engineer from DCX

and another from its fuel-cell stack supplier, Ballard Power Systems, was operating in the capital. By the end of September 2007 the accumulated demonstration mileage was over 84,000 km, and three fuel-cell buses had run for two years safely and smoothly on a standard bus route in Beijing with no emission, low noise and low vibration.

### *Hydrogen infrastructure*

Beijing Hydrogen Park opened its first permanent hydrogen refuelling station for FCBs in November 2006. The park, located about 15 km from the Olympic stadium, is a demonstration site for new energy development. It was built as part of the Fuel Cell Bus Commercial Demonstration Project supported by the UNDP, the GEF and MoST.

The refuelling station, built by BP and Sino-Hytec with technology from Air Products, is designed to meet early vehicle-fleet fuelling requirements by providing the customer with flexibility in using hydrogen generated on-site or a distributed hydrogen supply.<sup>6</sup> It served the three DCX Citaro fuel-cell buses tested in the first phase of the China/GEF/UNDP demonstration project, and provided a learning experience for the future development of hydrogen infrastructure. In addition, Shanghai is working on its own hydrogen infrastructure project in preparation for the World Expo, which will be held there in 2010. A refuelling station is located in Anting New Town, near the Shanghai International Auto City; it has the capacity to fuel three fuel-cell buses with 45 kg of hydrogen each and 20 fuel-cell automobiles with up to 3 kg of hydrogen each (*Fuel Cell Today*, 2007).

### The next phase

Despite the speed with which China is moving down its learning curve, there is still much to be done. Figure 15.4 illustrates the current situation, the next step and the targets for a set of key parameters to be achieved in fuel-cell vehicle R&D by 2020, the year by which 1,000 FCVs are to be commercialized.

Public education and awareness efforts have played a role in strengthening support for the move towards hydrogen fuel-cell vehicles in China. Recently there have been many reports in the media on the progress being made in developing hydrogen fuel cells, and the public are becoming more interested in FCV exhibitions and demonstrations. There is also a rise in interest among private companies. More local governments have begun to sponsor FCV demonstration programmes. Public awareness-

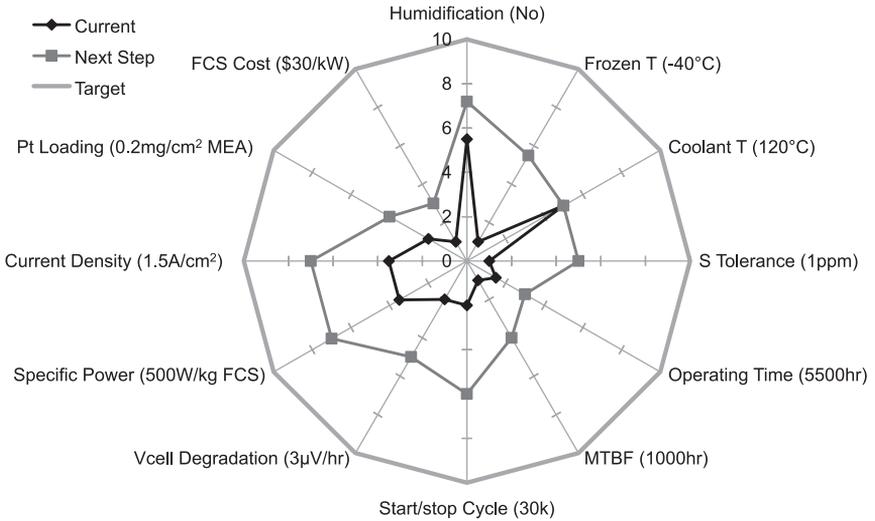


Figure 15.4 Targets for the next phase

raising initiatives, such as the use of fuel-cell buses at the 2008 Olympics, will reinforce this trend.

International cooperation has been another area in which efforts have recently been made. In 2003, for example, China became one of the three developing countries to join the International Partnership for the Hydrogen Economy (IHPE), which brings together a number of OECD member countries that are active in the development of hydrogen fuel cells and HFC vehicles. Through the IPHE, China has become a participant in international standard setting in this emerging industry.

In addition to the partnerships discussed earlier in this chapter, collaborative projects have been undertaken with a number of other international partners. Through its partnership with Hydrogenics, a Canadian company producing fuel cells and fuel-cell testing equipment, China is learning more about how to test Chinese-made fuel cells and stacks and develop testing benches. Samsung and the DICP have created a joint laboratory for fuel-cell research and development. In July 2006, to speed up the learning process with respect to the integration of fuel cells into vehicles, Ballard Power Systems and the Shanghai Fuel Cell Vehicle Powertrain company signed a memorandum of understanding for the supply of fuel cells and power-trains by Ballard and future cooperation on the development of fuel-cell vehicles for demonstration and field-trial programmes in China. General Motors signed a cooperation memo with

SAIC on fuel-cell vehicles, while Volkswagen has entered into a cooperative agreement with Tongji University on fuel-cell vehicles.

Chinese efforts to collaborate internationally reflect the recognition that fuel-cell vehicles represent a solution to environmental and oil-dependency problems. Through collaborative ventures, opportunities for FCV testing across different applications are widened. Such testing and demonstration projects are important ways to accumulate the experience and basic data for future research in overcoming technical cost and reliability barriers in order to meet the roadmap's goals. Collaboration also helps to build local knowledge networks through which R&D costs can be reduced, thus expanding market opportunities more rapidly.

## Notes

1. There was also a collaborative agreement between MoST and the government of Guangdong to co-fund research on stationary fuel-cell technology from 2004 to 2007.
2. The information in this paragraph comes from the presentation and answers to questions at the UNU international meeting in Maastricht in November 2005, the UNDP-GEF website and Beaudet (2004).
3. For additional information see [www.chinafcv.org/index-english.html](http://www.chinafcv.org/index-english.html).
4. For additional information see [www.chinafcv.org/index-english.html](http://www.chinafcv.org/index-english.html) and [www.chinafcv.org/chinafcv\\_en/description/2003/1175598665111161.htm](http://www.chinafcv.org/chinafcv_en/description/2003/1175598665111161.htm).
5. See [www.chinafcv.org/xmjb/040112issue4\\_3.htm](http://www.chinafcv.org/xmjb/040112issue4_3.htm).
6. See [www.airproducts.com/PressRoom/CompanyNews/Archived/2006](http://www.airproducts.com/PressRoom/CompanyNews/Archived/2006).

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## 16

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# Developing a strategy for the application of emerging hydrogen and fuel-cell technologies in Nigeria's transport sector

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## Introduction

Nigeria is by far the most populous African country. Rich in resources and with estimated gross domestic product of \$85 billion in 2005, it is the second largest economy in Africa after South Africa (Fitch-ratings, 2006). In spite of its huge earnings from the petroleum sector over the past few decades, estimated at over US\$300 billion, per capita income in 2005 remained very low, at US\$650. This reflects Nigeria's large population plus decades of suboptimal growth and substantial exchange rate depreciation. Agriculture and oil dominate both production and export. In 2005 oil accounted for around one-quarter of gross domestic product (GDP), 85 per cent of government revenue and over 90 per cent of export earnings. Agriculture accounted for 40 per cent of GDP, down from 60 per cent in the 1960s (Andrew and Schulz, 2005).

One of the challenges for the present leadership of Nigeria is the transformation and modernization of the Nigerian economy. Nigeria is blessed with substantial human and natural resources, including one of the highest reserves of gas and oil deposits outside the Middle East. The economic reforms embarked upon in the last few years are geared towards repositioning the Nigerian economy for sustained growth that will transform Nigeria into a middle-income country within a generation. The new vision of the country is embodied in a government document called NEEDS – National Economic Empowerment and Development Strategies (National Planning Commission, 2004). The key objectives of

NEEDS are wealth creation, employment generation, poverty reduction and value reorientation.

The transport sector has a significant role to play in meeting the development challenges ahead. Currently, Nigeria's transportation infrastructure is quite poor, even by developing country standards. To provide for the anticipated growth and meet national developmental aspirations, it is generally accepted that adequate, efficient, reliable and affordable passenger and freight transport services are essential. Therefore, as a developing country, the next few years will see Nigeria striving to improve its transportation sector to a level comparable to world standards.

Presently, the transport sector is the largest consumer of commercial energy in Nigeria. Gasoline and diesel are the two major fuels used in the sector. The policy of cheap energy prices and massive importation of fuel-inefficient second-hand vehicles from Europe and America have contributed to the rising consumption of petroleum products. The dependence of the transport sector on these products has put tremendous pressure on the government to increase oil production, particularly as a rising proportion of export earnings and government revenue has to be spent on the import of gasoline and diesel<sup>1</sup> as a result of low capacity utilization in domestic refineries. In addition, the almost exclusive dependence on petroleum fuels by the transport sector is leading to increased air pollution and greenhouse gas (GHG) emissions.

Thus among the various issues that policymakers have to confront in transportation policy are, first, adoption of an efficient transportation modal structure that will be consistent with the rising urban population in Nigeria, and second, promotion of an appropriate mix of energy use in the transport sector that will reduce pollution and promote efficiency. In the past, environmental considerations have not featured prominently in the strategies for developing the transport sector; and this cannot be isolated from the low level of awareness by decisionmakers of the impact of energy utilization on air pollution and GHG emissions.

The challenge is therefore to make decisionmakers understand the various dynamics involved in effectively coupling national developmental aspirations to environmentally friendly policies in the transport sector. Such policies would enable the country to benefit from emerging energy technologies that could provide avenues to develop climate-friendly strategies for the sector and at the same time be adequate to meet the projected economic growth. In this scenario, it is expected that policymakers would be motivated to seek for ways to apply emerging technologies such as hydrogen and fuel cells to the economy, and more specifically in the transport sector.

The next section examines trends and patterns of energy use in the transportation sector; this is followed by an examination of current and

future policy thrusts in the sector, especially focusing on the potential for adoption of new and emerging energy technologies. The chapter also highlights current levels of preparedness in the country to benefit from the emerging technology, and the implementation issues.

## Transport sector in Nigeria: An overview of trends and patterns of energy use

The transport system of Nigeria has evolved over a long period of time, and witnessed rapid growth in the 1970s and early 1980s mainly as a result of a massive inflow of petrodollars into the economy. At the same time, rapid population growth, a rising trend in rural-urban migration, rising social aspirations and urgent desires by the political leadership to modernize the economy exerted increasing demands on the transport system. However, the significant investment in the system in the 1970s could not be sustained due to the economic downturns that followed the collapse of the world oil market in the mid-1980s.

Evidence of weak investment in the transport system after the 1970s can be seen in the inadequate maintenance of roads and slow addition of new roads. The collapse of real income for Nigerians after the introduction of the structural adjustment programme (SAP) in 1986 led to a preponderance of old vehicles and poor maintenance of existing vehicles, as most Nigerians were unable to purchase new vehicles and turned to imports of second-hand vehicles from developed countries. This resulted in a large presence of fuel-inefficient vehicles on Nigerian roads, with very costly pollution and environmental consequences. In the case of railways, lack of necessary resources to keep tracks, rolling stock and maintenance facilities in reasonable condition resulted in very serious deterioration of the system. Similar problems affect inland waterways, constraining their ability to perform useful functions.

### *Structure of the transport sector in Nigeria*

The country's transport sector is dominated by roads. Trends in the road transport subsector in Nigeria, as in most other developing countries, have shown marked increases in private transportation driven by higher incomes<sup>2</sup> and the desire for personal mobility, especially due to inadequate public transport systems. Fall-outs from growth in urban transport activity and rapid growth in urban population include intense road congestion, resulting in unproductive time delays and increased fuel consumption and emissions. Lagos, Port Harcourt, Ibadan and a number of other major cities in the country exemplify this development.

Table 16.1 Transportation basic data, 2000–2004

	2000	2001	2002	2003	2004
<i>Road transport</i>					
Length of roads (km)	33,996	34,122	34,403	34,403	34,403
Principal roads (km)	15,121	15,407	15,688	15,688	15,688
Paved roads (km)	28,078	27,677	27,957	27,957	27,957
Of which bad portion (km)	5,918	6,446	6,446	6,446	6,466
Motor vehicle population (000)	1,288	1,444	1,734	2,074	2,176
Of which newly registered	156	196	290	340	402
Number of road accidents	12,705	13,801	14,267	14,983	14,279
Of which persons involved	27,198	29,544	30,542	32,175	22,248
Of which persons killed	6,521	8,012	2,620	2,817	5,351
<i>Air transport</i>					
Loaded freight (000 tonnes)	11,923	12,726	18,052	19,972	22,518
Unloaded freight (000 tonnes)	15,302	15,266	20,758	55,160	63,158
Departing passengers (no.)	533,585	624,174	652,019	646,777	733,445
Transiting passengers (no.)	163,776	139,503	91,944	31,261	37,857
Arriving passengers (no.)	519,987	609,984	611,307	614,770	711,781
Aircraft arriving (no.)	6,996	7,009	6,930	7,869	9,097
<i>Maritime transport</i>					
Loaded goods (000 tonnes)	8,349	9,445	7,988	9,892	10,634
Unloaded goods (000 tonnes)	15,991	21,150	21,823	23,175	27,569
Arriving ships (no.)	5,157	4,725	4,621	5,287	6,278
Of which tankers (no.)	693	905	760	837	998
Arriving passengers (no.)	1,868	647	338	475	506
Departing passengers (no.)	1,565	573	248	312	329
<i>Railway transport</i>					
Length of railway lines (km)	3,505	3,505	3,505	3,505	3,505
Locomotives (no.)	49	45	44	46	46
Carriages (no.)	235	248	246	251	251
Wagons (no.)	1,229	1,363	1,382	1,405	1,410
Passenger traffic (000 passengers/km)	1,525,946	1,284,026	1,064,344	1,130,093	1,157,042
Goods traffic (000 tonnes/km)	116,837	132,713	98,190	125,718	139,871

Source: Nigeria Bureau of Statistics (various years).

Table 16.1 shows basic data on transportation in Nigeria from 2000 to 2004. In 2000 the number of vehicles in the country was estimated to be 1.3 million, representing 11.2 vehicles per 1,000 people. The road network density was 36.8 km per 1,000 km<sup>2</sup>. Figures for 2004 show a marked

increase in some of these indices. The number of vehicles rose by nearly 51 per cent to 2.2 million, with a vehicular density of 16.85 vehicles per 1,000 people and a road network density of 37.2 km per 1,000 km<sup>2</sup> (FOS, 2005), showing an increase of 1.09 per cent over 2000. These figures are still quite low even by African standards. Nonetheless, over the period 1985–2003 the transport sector accounted for between 42 and 53 per cent of total GHG emissions in the country (Davidson, 1993; Ministry of Environment, 2003).

### *Patterns and trends in transport energy use*

The transport sector is the single largest user of commercial energy in Nigeria. On average, the sector accounted for over 50 per cent of commercial energy consumption between 1970 and 1990 (Adegbulugbe, 1990). This pattern remains unchanged, as can be seen in figure 16.1. The presence of fuel-inefficient vehicles, congestion and the problems of the industrial sector explain the continued dominance of the transport sector in overall commercial energy use in Nigeria.

The transportation mode in Nigeria is skewed heavily in favour of small cars rather than rail or other mass-transit systems. Cars absorb over half of Nigeria's transport energy. Nigerian cars require about twice the fuel input as in other countries, mainly as a result of heavy traffic congestion in urban areas and low pump prices in the past (Akinbami and Fadare, 1997). Table 16.2 shows the vehicular fuel intensities in Nigeria and selected countries in sub-Saharan Africa. The table clearly demonstrates the high degree of inefficiency in fuel utilization in the Nigerian transport sector.

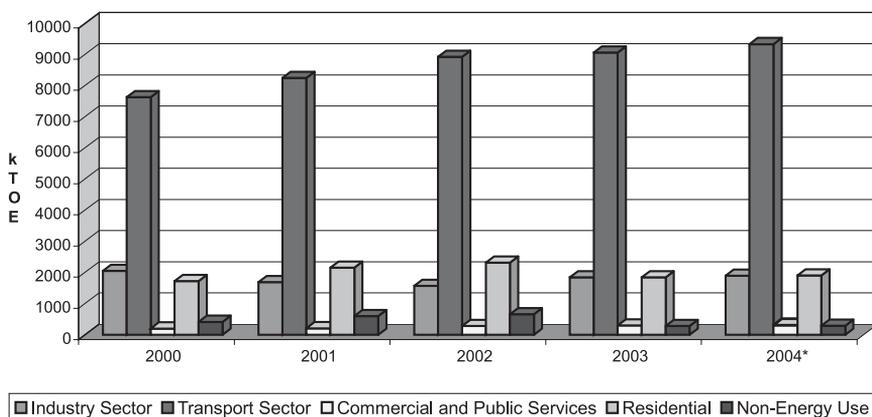


Figure 16.1 Sectoral commercial energy utilization

Table 16.2 Comparison of fuel intensity per vehicle in selected African countries

	Gasoline per car		Diesel per truck or bus		Total fuel per vehicle	
	1971	1987	1971	1987	1971	1987
Nigeria	0.19	0.12	0.35	0.05	0.24	0.09
Côte d'Ivoire	0.07	0.03	0.08	0.15	0.07	0.07
Kenya	0.04	0.07	0.12	0.04	0.07	0.06
Ethiopia	0.04	0.07	0.11	0.04	0.07	0.13
Zambia	0.08	0.04	0.04	0.03	0.06	0.03
Zimbabwe	0.04	0.02	0.08	0.12	0.05	0.02

Source: Davidson (1993), cited in Akinbami and Fadare (1997).

It is also important to mention that fuel utilization in the road transport sector is dominated by gasoline, which accounts for over 80 per cent of total fuel consumed in the sector, with diesel accounting for the balance (fig. 16.2). This has serious environmental implications because increased fuel use leads to higher levels of air pollution and GHG emissions. Two factors have contributed to this: a rise in the number of motor vehicles and an increase in travel time due to road congestion (UNEP, 2002). Motor vehicles produce 80–90 per cent of the lead in the environment, even though unleaded gasoline has been available for some time in most countries in the region (ibid.). Deficient public transport systems, as

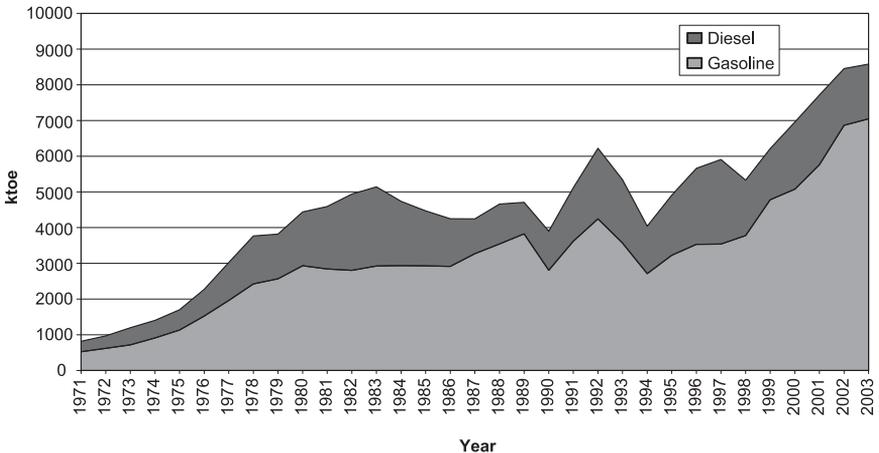


Figure 16.2 Transport fuel consumption by type

well as the separation of homes from workplaces in cities, have resulted in more frequent and longer journeys. Worsening air quality, the rising number of automobile accidents and increased congestion are taking their toll on the quality of life of the people (*ibid.*; Walsh, 2003).

In recent times both state and federal governments have taken several steps to address the issues of transport situations and air quality problems faced in a number of the heavily populated cities in the country, including a ban on the import of vehicles that are over eight years past their production date. However, Nigeria's porous international borders still permit illegal importation of such vehicles. Secondly, on the drawing boards are efforts to modernize and develop the country's railway system. To achieve this goal, Nigeria has signed a memorandum of understanding (MOU) with some Chinese and Korean firms to construct new rail lines across the country. In a related development, Lagos, the commercial centre of the country with a population in excess of 9 million, under the government of Lagos state, is currently contemplating development of an intra-city railway system. Similarly Abuja, the Federal Capital Territory (FCT), also has on the drawing board a light-rail system to connect satellite towns to the FCT.

### Prospects for hydrogen-cell application in the Nigerian transport sector

The NEEDS document envisaged a significant role for the transport sector in transforming the Nigerian economy. Hence, the sectoral reforms include the completion of a 3,500 km network of roads by 2005, increasing to 4,000 km in 2007. The Road Maintenance Agency is to be strengthened to overhaul and rehabilitate some 500 roads per year. The government also aims to develop the country's seaports to handle modern shipping activities, and to upgrade the railways and achieve total radar coverage of Nigerian airspace (National Planning Commission, 2004).

Thus there are indications that future demand for transport services to support national economic development is going to be large. Coping with this demand in Nigeria will require the matching of transport and environmental objectives. The current dominance of road transport in the total transport system is likely to continue in the foreseeable future. Figure 16.3 shows the projected trend in motive power for the road transport system till 2015. It is anticipated that there will be more than a threefold increase in motive power demand between 2003 and 2015 in order to meet the expected social and economic growth of the economy.

How to supply this motive power remains a critical policy area in the future. Various least-cost and environmentally beneficial options for

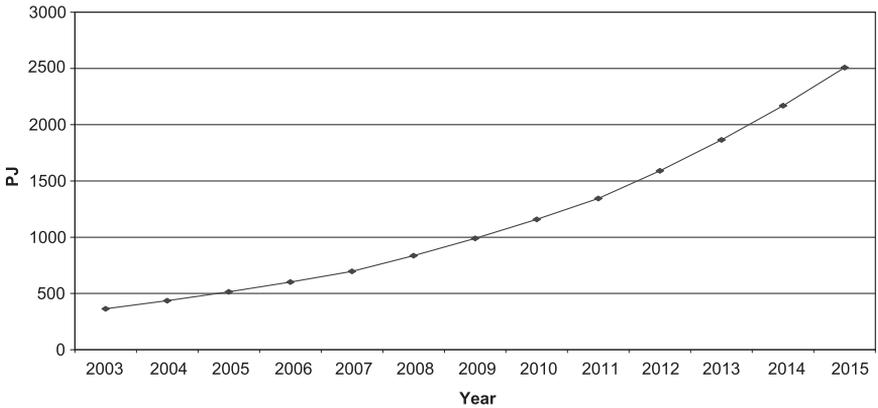


Figure 16.3 Projected trend in motive power for the road transport sector

tackling anticipated transport sector growth in Nigeria should be examined. There is a need to integrate several options into the broader transportation agenda, including fuel quality improvements, fuel efficiency, more efficient mass-transit systems, improved railway transportation and the use of compressed natural gas (CNG), among others (Figueroa, Davidson and Mackenzie, 1998).

The government of Nigeria is working towards harnessing all options to address all issues related to the problems in the energy sector, which includes the transportation agenda. For instance, the government has set 2008 as the deadline for banning natural gas flare-out to reduce GHG emissions to the atmosphere and cut the wanton wastage. To promote development of a local market for natural gas, the natural gas sector within the Ministry of Energy is now headed by a minister of state. Furthermore, there are ongoing legislative and policy reforms to support the development of the internal market for natural gas. In the new gas-pricing policy framework being developed by the federal government, CNG has been identified as one of the strategic sectors, along with power and fertilizers, that will enjoy preferential gas pricing of US\$0.10/MMBTU.

The transportation sector provides an excellent area for technological leapfrogging. Recent breakthroughs in fuel-cell technology offer a great opportunity in this regard. This technology makes electric vehicles possible, and also has a significant potential to increase fuel efficiency and reduce the current high level of pollution associated with the transport sector in Nigeria. Fuel-cell technology can be used across a wide range of transportation modes, including trucks, cars and buses.

Presently, fossil fuels provide the vast bulk of the energy used in the Nigerian transport sector, and are likely to do so for a long time. How-

ever, in the future transport fuel resources will have to be diversified to extend access to mobility to a larger proportion of the population, while curbing emissions. As part of achieving this goal the federal government has approved a national policy on the use of blended methanol with gasoline as a transport fuel. In the long term, however, it is anticipated that hydrogen and fuel cells could meet this challenge. Moreover, it is expected that decreasing fuel-cell prices in the future will erode whatever price advantage gasoline presently enjoys.

Realizing the benefits that could accrue from fuel-cell technology, the government had taken steps to prepare the country for adoption of this emerging technology in the near future, as embedded in the energy master plan document that has been finalized by the Energy Commission of Nigeria (ECN/UNDP, 2005) and approved by the government. The document details how to achieve the vision of promoting renewable energy, including hydrogen fuel, in the country. Nigeria depends on importing vehicles, as the local assembly plants are operating at a very low level of capacity utilization. Hence, more rapid deployment of the new technologies abroad will provide some inducement for local adoption of the technology. Moreover, the cost of vehicles using the new technology will be a major factor in adoption of hydrogen fuel-cell vehicles in a poor country like Nigeria.

There are several other challenges that will have to be overcome for fuel cells to have widespread application in a developing country like Nigeria: first, the distribution and refuelling infrastructure must make hydrogen accessible to potential users at affordable prices; second, appropriate regulatory policies and standards must be developed and put in place to ensure safe hydrogen production, storage, distribution and use; and third, an enlightenment programme to overcome public perceptions of the costs associated with hydrogen must be developed.

### *Cleaner energy and the Nigerian transport system*

Nigeria is both an oil and a gas country. The oil reserve is estimated to last about 50 years, while the gas reserve is projected to last for more than 100 years. Despite these reserves, however, Nigeria has a vision of an economy driven increasingly by renewable energy. This is because over the next 20 years the population is expected almost to double, with aggregate energy demand more than tripling. This rapidly growing energy demand will in turn create opportunities for renewable energy. In addition, only 40 per cent of the entire population currently has access to electricity. Conventional energy sources alone will not be able to meet the challenges of increasing access to energy at affordable costs and in a flexible manner over the coming years. The rapidly growing

energy demand in rural areas is already driving the market for photovoltaics (PVs), micro-hydro and windpower plants in meeting demand for rural water supply, lighting, health services and the needs of micro-enterprises (IPA Consulting et al., 2002).

Electric power sector reform is also expected to create incentives for renewable energy deployment into the system. Grid extension may not expand rapidly to rural areas under market forces, which will make renewable energy an alternative for off-grid power supply to provide a solution.<sup>3</sup> In Nigeria, likely renewable candidates for power generation include small hydropower, solar PVs and co-generation technologies, with wind and biomass providing additional opportunities.

Hydrogen is expected to provide one solution to the energy needs of Nigerians at a future point when fossil fuels will no longer be available. However, complete transition to a hydrogen economy will take several decades. There is presently a lack of know-how to deliver clean, affordable, safe and convenient energy from hydrogen for transportation, electricity or stationary uses. There is a need, however, for Nigeria to start to plan for a transition to a hydrogen economy. Even though this form of energy is not competitive in the short run in Nigeria, areas that would need to be immediately addressed for its introduction include public perceptions of the safety of hydrogen, the low cost of fossil-fuel alternatives, institutional and human capacity development, and improvement in research, development and dissemination (RD&D).

### *R&D strategies to benefit from emerging technology and develop local capacities and capabilities*

The policy statement on energy R&D for Nigeria states that “the nation’s energy resources shall be developed and utilized on a self-sustaining basis through appropriate tools of research and development and the profitable application of relevant results” (Federal Ministry of Science and Technology, 2005). This policy thrust gave rise to two underlying objectives:

- to initiate and promote energy-related research and development programmes, and ensure that such programmes are application oriented and market driven
- to promote participation in R&D programmes/projects by Nigerians in all areas of energy exploration, development and utilization in an environmentally friendly manner.

To achieve these objectives, the strategies noted in the document include:

- setting up and maintaining a comprehensive information system on available renewable energy resources and technologies
- endogenizing hydrogen production and application technologies

- developing and promoting capabilities within the nation's energy research systems for the design and fabrication of efficient energy devices and technologies for the utilization of the nation's renewable resources of wind, solar, biomass, nuclear and hydrogen
- establishing a pilot plant for the demonstration and dissemination of renewable energy devices and technologies to promote their adoption for market penetration
- monitoring and assessing international developments in all energy areas, and initiating and maintaining local capability for their sustainable application
- initiating and promoting energy educational programmes and research activities in tertiary institutions
- developing and implementing R&D in the optimal utilization of various energy resources to minimize associated adverse environmental impact
- developing a scheme of incentives to encourage producers and users of renewable power systems.

However, for the nation to achieve any meaningful result from embarking upon any strategy for the use of emerging energy technologies, priority must be given to the development of local capacities and capabilities. That is why the success of the second objective and the second and third strategies listed above will become key in judging the overall benefits to be derived by Nigeria from adopting a proactive stance on the issue of an emerging technology in the transport sector.

In order to quantify the benefits of strategies for future energy systems and compare the competitiveness of emerging technologies to conventional ones, it is necessary to adopt suitable criteria. This chapter uses the criteria proposed by Nitsch (1988) as the basis for assessment. Therefore, for Nigeria to achieve the objectives of the energy R&D policy, the following must be considered.

- Will the emerging technology (hydrogen energy for the transport sector) be able to supply a desired energy service comparable to the conventional supply systems?
- Will this allow Nigeria to expand and diversify its future energy supply?
- Will it be environmentally friendly?
- What will its economic impact be?
- Will it be socially compatible?

In addition to these criteria, economic and financial returns will be an important factor. The system must guarantee appropriate returns to investors in order to provide sufficient incentives for private sector participation. The plan also stresses the need to endogenize this technology shift in the near future through the building of human and institutional capacity, as Nigeria currently has no adequate expertise in hydrogen

fuel-cell technology utilization. Furthermore, to sustain the renewable energy programme for the country, there must be a clear R&D effort backed by adequate funding, coupled with international collaboration and the development of private sector partnerships.

These are some of the issues that are critical to the future adoption of hydrogen fuel-cell technology in Nigeria. Nigeria does not presently have all the domestic capabilities to develop and implement these alternatives. However, a roadmap is being developed to build the bases for the transition to a cleaner energy and transport system. This is briefly presented in the next section.

### A strategic approach to the implementation of renewable energy/hydrogen

Entry of renewable energy (RE) and hydrogen into the energy economy of Nigeria will require carefully thought-out strategies and approaches. This will not only ensure a smooth entry, but also allow for sustained momentum once implementation starts. This section therefore draws heavily on the renewable energy master plan being developed as a roadmap for achieving Nigeria's vision on RE development, which also includes thinking about hydrogen. The key strategic and implementation issues discussed in the document are listed below.

- *Policy, legal and regulatory framework.* This entails the articulation of clear policies, rules, legislation, roles and responsibilities of the various stakeholders at every stage of the energy flow, from supply to the end-user sectors, needed to promote renewable energy technologies (RETs).
- *Create a level playing field.* This entails the removal of hidden subsidies and internalizing external costs of fossil fuels.
- *Have a renewable portfolio standard (RPS).* This means that a policy is put in place setting realistic targets of RE contents for the overall energy supply to specific areas.
- *Have fiscal incentives.* This involves the application of all innovative fiscal incentives (such as custom duties exemption, tax credits, capital subsidies, etc.) for RE development and deployment to the overall energy mix for the country.
- *Have a market incentive policy for RE.* REs are not yet cost-effective globally. This is a major obstacle to their entry into the energy market, and calls for highly innovative policy incentives to encourage widespread participation.
- *Develop power purchase agreements (PPAs) for REs.* Putting a PPA in place gives electricity utilities and RE-based producers a clear understanding of their responsibilities and rights. All bottlenecks that may

be encountered by RE-based producers would also need to be properly looked into in the PPAs.

- *Integrate RE into non-energy-sector policies.* This involves integrating RE into non-energy-sector policies in key areas such as rural development and electrification, poverty alleviation, agriculture, transport, industry and infrastructural development.
- *Establish an RE development agency.* This agency is primarily to coordinate activities between government ministries, parastatals and agencies responsible for rural development and RE development.
- *Establish an RET testing centre.* This centre is concerned primarily with the certification of all hardware connected with RE development in the country. In addition, the centre will gather data on performance of deployed RETs.
- *Mobilize funds from multilateral and donor communities for RE in Nigeria.* It is anticipated that the country will tap into existing programmes of multilateral organizations with portfolios for RE projects.
- *Create an enabling investment climate for REs.* To achieve the RE programme in the country the government alone cannot provide the needed funds. Mobilizing private sector (local and foreign) participation will involve creation of an enabling environment conducive to investments.
- *Encourage inter-agency collaboration on REs.* There is a need to depart from current governance structure on RE. An agency with clear responsibility for developing RE in the country needs to be established.
- *Build human and institutional capacities at all levels.* To sustain the implementation of an RE/hydrogen economy will require the building of human and institutional capacities at all levels in relevant scientific, engineering and technical skills for the design, development, fabrication, installation and maintenance of RE infrastructure.
- *Create avenues for public awareness of opportunities in REs.* The present level of awareness of opportunities offered by RE and its technologies needs to be aggressively addressed.
- *Strengthen research, development and dissemination of RETs in the country.*
- *Encourage the emergence of RE professional/industry associations.* These associations are expected to be a driving force for the promotion of RETs in the country.

## Conclusion

This chapter examines current trends in energy use in the Nigerian transportation sector. It also discusses the current level of preparation of the country for the adoption of newly emerging technologies such as

hydrogen fuel cells. The chapter highlights challenges that must be overcome to enable the country to benefit from this emerging technology and harness the opportunities it provides to achieve targeted goals for energy efficiency and diversification in the transport sector.

As the chapter shows, a renewable energy master plan that includes hydrogen is being developed, but the specific strategy and policies for its implementation have yet to be adopted. It is anticipated, however, that the new direction the federal government is taking on renewable energy will better enable the nation to take advantage of the opportunities presented by recent developments in fuel-cell technology, and also to be able to integrate it into the transport energy policy matrix. Though there are no immediate efforts to pursue the use of renewable energies due to the continuous availability of relatively cheap fuels – gasoline and diesel – there is hope that policymakers will seek to develop more environmentally friendly and efficient energy sources in the near future.

In this regard, the research community needs to be more proactive in bringing the opportunities in fuel-cell technology more forcefully to the policy arena. This is presently lacking. To the extent that leading international scientists in this area collaborate with partners in developing countries like Nigeria through demonstration projects, for example, the viability of the technology and areas for its application will become clearer. There is also a need for concerted efforts between local and international levels to break the current apathy in both policy and academic communities in Nigeria towards the adoption of emerging technologies such as hydrogen fuel cells.

## Notes

1. For a detailed discussion of the Nigeria National Petroleum Corporation (NNPC) and its development strategies see chapter 7 in this volume.
2. Income has been shown as a major determination of the size of motor vehicle fleet (Walsh, 2003). See also chapter 8 on Egypt and chapter 15 on China in this volume.
3. See also the discussion of off-grid electric power in South Africa in chapter 17 of this volume.

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# Hydrogen and fuel-cell technology issues for South Africa: The emerging debate

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*Boni Mehlomakulu*

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## Introduction

By establishing the Department of Science and Technology in 2004, the government of South Africa had aspirations to achieve mastery of technological change in the country's economy and society. The department is tasked with identifying and developing the lead sectors that will potentially expand the base for the creation of wealth and position the country favourably to compete successfully within a dynamic knowledge economy. To this end, the department identified hydrogen and fuel-cell technologies as a "frontier science and technology" platform that could potentially change the innovation course around South Africa's natural resources and yield multiple social and economic benefits for its citizens.

Hydrogen and fuel-cell technologies are believed to be the energy solutions for the twenty-first century, enabling clean, efficient production of power and heat from a range of primary energy sources. The transition to a future "hydrogen economy" is expected to reduce dependency on oil and gas greatly, and reduce carbon dioxide emissions. In the spectrum of technologies that interconnect to shape the global hydrogen economy vision, platinum plays a crucial role as a catalyst that converts hydrogen to electricity. According to the International Platinum Association (2003), no other material has been shown to be as effective as platinum in proton-exchange-membrane fuel cells (PEMFCs). The significance of

this fact raises multiple issues for South Africa, with its endowment of platinum resources.

This chapter analyses the potential role for hydrogen and fuel-cell technologies in addressing energy supply and developmental challenges facing South Africa. The chapter successively discusses issues related to energy policy, quality, access and use; the rationale for South Africa's interest in hydrogen and fuel-cell technologies; the research, development and innovation support base for hydrogen and fuel-cell technologies in South Africa; and the themes emerging from the recently concluded hydrogen and fuel-cell technologies R&D strategy.

### The South African energy sector at glance

South Africa's energy sector is critical to the economy, contributing about 15 per cent to the gross domestic product (GDP) and employing about 240,000 people. Coal accounts for about 79 per cent of primary energy consumption. The majority of this is used to generate electricity, while a significant amount is channelled to synthetic fuel and petrochemical operations. Large coal reserves have made it possible for South Africa to offer cheap electrical power by international standards – it is one of the cheapest electricity suppliers in the world. South Africa has no significant oil reserves, and relies on coal for most of the oil production from its highly developed synthetic fuels industry. The overall picture of energy sources is depicted in table 17.1.

Crude oil is imported into the country. Renewables are mostly in the form of fuelwood used by rural citizens for cooking and heating. South African households use about 17 per cent of the country's energy. Industry (which includes minerals processing), commerce and mining use in excess of 50 per cent of commercial energy, while transportation uses a further 28 per cent, mainly liquid fuels (table 17.2).

Table 17.1 Primary energy supply, 2000

Energy source	Contribution (%)
Hydro	<1
Nuclear	3
Natural gas	2
Renewables	6
Crude oil	10
Coal	79

Source: Department of Minerals and Energy (1998).

Table 17.2 Final energy use by sector, 2000

Sector	Usage (%)
Industry	41
Transport	28
Residential	17
Mining	6
Commerce	4
Agriculture	3
Other	1

*Source:* Department of Minerals and Energy (1998).

### *Electricity sector*

The origins of the electricity supply industry in the first years of the twentieth century were driven by the needs of the booming mining industry in South Africa. The energy sector has supported massive investments in heavy industry and mining. Today, much of the manufacturing sector is linked to mining activities through mining input industries and minerals processing. All of these activities are energy-intensive, relying on the availability of cheap coal and electricity. The presence of the “minerals-energy complex”, with its links to mining products and reliance on low energy prices, underpins much of the South African economy. The electricity supply industries of Southern Africa are dominated by the state-owned utility of South Africa, Eskom, which generates around two-thirds of the electricity produced in the whole of Africa and is extending its transmission grid north into neighbouring sub-Saharan countries. It already supplies electricity to Lesotho, Swaziland, Botswana, Namibia, Mozambique and Zimbabwe.

Generation is primarily coal-fired, but also includes a nuclear power station at Koeberg, two gas-turbine facilities, two conventional hydroelectric plants and two hydroelectric pumped-storage stations. Eskom also owns and operates the national transmission system. Massive power station projects initiated in the 1960s and 1970s, with the assumption of continued rapid increases in electricity demand, left the national utility with large excess capacity in the 1980s and 1990s, and this has helped to keep electricity prices low (South Africa, 2003). With the political change that took place in South Africa in the mid-1990s, the government and Eskom undertook a massive expansion of the national grid to reach areas that were previously marginalized by the “apartheid” ruling, i.e. black townships and rural areas. Millions of houses were electrified. Nonetheless, the increasingly high cost of extending the grid to rural areas that are remote from the existing network, have a low density of houses and



time needed to commission a new plant, it became clear that the electricity generation system was vulnerable.

Eskom has 24 power stations, located in different parts of the country. The different layers on the graph in figure 17.1 represent the actual power stations, the *y*-axis represents the various power stations' capacity and the *x*-axis represents the expected lifespan of each station. Nuclear energy does not play a major role in South Africa – accounting for about 3 per cent of all energy and 7 per cent of electricity. The nuclear plant at Koeberg was commissioned in 1984, and is South Africa's and Africa's only commercial nuclear installation. It has a capacity of 1,930 MW. South Africa serves on the board of governors of the International Atomic Energy Agency, as it is the most advanced African country in the field of nuclear technology.

The South African economy is currently going through the longest sustained upswing in its history. Growth in GDP per capita, which was less than 1 per cent a year between 1994 and 2003, accelerated to 3.1 per cent in 2003, 4.8 per cent in 2004 and 5.1 per cent in 2005. With the Accelerated and Shared Growth Initiative for South Africa (ASGI-SA), the government aims to improve on the country's remarkable economic recovery, raising economic growth to 6 per cent and halving poverty and unemployment by 2014. Energy supply infrastructure, as a primary input to economic development, will need to keep up with stay ahead of the energy demand curve over the next 10 years if the economic growth goals are to be realized.

In his 2007 State of the Nation address, the President of South Africa, Thabo Mbeki said:

in line with the National Industrial Policy Framework which has now been completed, we will develop programmes to facilitate investments in sectors along the supply chain for our infrastructure programmes, including capital goods in ICT, transport and energy: with regard to energy, we will also expedite our work to ensure greater reliance on nuclear power generation, natural gas and the various forms of renewable sources of energy.

### *Liquid fuels sector*

Until the 1990s an upstream oil industry did not exist in South Africa. There are currently small productive oil and gas fields off the south-east and west coasts, providing raw materials for a synfuels plant at Mossel Bay; but South Africa relies heavily on imported oil. Most countries view the oil industry as a strategic industry that is vital to the development of the economy. Consequently, there has been a high degree of intervention, regulation and protectionism in the industry worldwide as

countries have sought to reduce their dependence on imported oil and nurture the domestic production of refined petroleum products.

The drive towards self-sufficiency was a key feature of the evolution of the liquid fuels industry in South Africa because of the country's increasing isolation and the imposition of sanctions during the second half of the 1900s as the world responded to the apartheid government's policies. This gave rise to the establishment of a refining industry through the provision of generous incentives to multinational oil companies to locate refineries in South Africa. More significantly, it also saw the establishment of a highly developed and unique synthetic fuels industry based on the country's abundant coal resources and offshore natural gas, and condensate production in Mossel Bay. Initially owned by government, the industry was built on the basis of what appears to be generous levels of government support for the technology, construction and continued operation of synthetic fuels manufacturing plants. The two major players are Sasol (coal to oil/chemicals) and PetroSA (natural gas to petroleum products). Sasol has the capacity to produce 150,000 bbl/d, and PetroSA produces 45,000 bbl/d – respectively meeting 23 per cent and 7 per cent of South Africa's petroleum products requirements.

Once regarded as an apartheid-era white elephant, Sasol today possesses the technology that may extend the deadline for the world's liquid-fuel crisis: the Fischer-Tropsch coal-to-oil technology that Sasol bought from Germany in the aftermath of the Second World War. Whereas Hitler had tried unsuccessfully to produce oil from coal for his war machine, Sasol has succeeded in converting low-grade coal into liquid fuels and high-end petrochemicals for more than half a decade. In an environment of high oil prices, opportunities are being explored for the technology to be transferred to other coal-rich countries such as China, India and the United States.

Continued R&D investments into the Fischer-Tropsch technology in South Africa resulted in the development of the gas-to-liquids (GTL) technology. This is a much more cost-effective and environmentally friendly process, and is geared towards the production of low-sulphur diesel using gas as a feedstock instead of coal. It is believed that, while oil reserves might be dwindling, there are huge uncommitted gas reserves worldwide. The demand for diesel is also increasing, and is expected to reach at least 18 million bpd by 2020. Sasol has recently commissioned a GTL plant, the Oryx GTL facility in Qatar, which is being expanded from its planned 34,000 bbl/d to 100,000 bbl/d, and has signed an agreement with Qatar Petroleum to develop another integrated GTL plant with an output of 130,000 bbl/d. In liquid fuels, South Africa thus has a number of options to explore, including biofuels and the possible expansion of synthetic fuels.

## The transport sector in South Africa

While most of the developed countries are turning to hydrogen and fuel-cell technologies to solve transport-fuels-associated challenges, the current passenger transport strategies in South Africa do not include hydrogen. This is explicable given that transport challenges in developing countries are more complex and basic than those in developed countries. Past land policies in South Africa resulted in poor communities being located furthest from work. In addition to being a burden on the poor, this resulted in the inefficient use of transport energy. Most of these communities used and continue to use minibus taxis, and the industry has grown in an almost totally uncontrolled manner. This has led to excessive route congestion and confrontation between competing operators. The government's minibus taxis recapitalization programme, currently being implemented, aims to introduce more control and governance into the informal taxi industry.

One of the major transport infrastructure programmes in South Africa is the development of the Gautrain rapid rail link, which commenced in 2005. This is a state-of-the-art rapid rail network planned in the Gauteng region of the country, which is the economic and legislature hub of South Africa. Traffic congestion between Johannesburg (economic capital) and Pretoria (legislature capital) is already threatening various economic activities. It is estimated that the Gautrain will reduce CO<sub>2</sub> emissions by 70,000 tonnes per year (Jensen, 2007).

Although hydrogen and fuel-cell technologies are presently not seen as part of the short- to medium-term solution to South Africa's transport challenges, the country hopes to contribute to the knowledge that will eventually drive the costs of the technology down, address safety issues and create a new energy paradigm in the world.

Liquid fuels, however, will continue to play a prominent role in the South African transport sector and economy. Various government departments have collaborated to create the necessary regulatory and subsidy policies to promote the use of biofuels. A 40 per cent rebate on the biodiesel fuel levy was introduced in 2002.

## Why is South Africa talking hydrogen?

History demonstrates that technological advances are the cornerstone of development, and developers and early adopters of new technologies enjoy great advantages. This has been evident for several centuries, as demonstrated by the transformation of society after the introduction of public

transport in the form of trains, trams and buses, followed in relatively rapid succession by the automobile, radio, the airplane, television, the computer revolution and the foundations of the internet. And the trend continues today as mobile and wireless technologies reach into previously inaccessible regions; all with the aim of empowering the average man and woman to make a contribution to their own empowerment and the societies in which they live and work.

Access to and knowledge about modern energy resources lies at the heart of all progress, and the plain fact is that it will be the countries at the forefront of energy innovation that will enjoy the full benefits of the technology. Advancing sectoral knowledge through targeted science and technology programmes has been recognized to have the potential to change the energy picture rapidly. The planning and implementing of relevant S&T activities can substantially improve South Africa's ability to transfer enabling technologies to specific developmental agendas at a much-increased rate and depth. Potentially this could also contribute to more rapid use of new energy sources such as hydrogen within Africa more broadly.

The challenge is always that research, innovation and knowledge generation do not come cheap. By and large, countries that engage in robust R&D are more likely to advance than countries that skimp in this area. In information and communications technologies (ICTs) terms, the gap is increasingly being referred to as the digital divide, and bridging this divide, or at least ensuring that it gets no wider, has become a priority focus for a growing number of African countries.

Although it may be hard to justify, given the subsistence nature of most economies in the region, Africa needs to face up to the clear necessity to realign itself with an innovation-based paradigm. Only sustainable local economic activity can provide the "activation energy" needed to uplift poor communities, currently locked in poverty with no escape trajectory. Creating affordable energy services can and should be used as a catalyst for this development, to enable productive economic activities, improvement in the quality of life and integration of energy services to improve access to water, health, connectivity and transport.

## Energy policy in South Africa

The energy sector in South Africa is governed by a white paper adopted in 1998 (Department of Minerals and Energy, 1998). The white paper gives an overview of the South African energy sector's contribution to GDP, employment, taxes and the balance of payments. The government

views the energy sector as crucial to successful and sustainable national growth and development, and the energy white paper sets out the following policy objectives:

- increasing access to affordable energy services
- improving energy governance
- stimulating economic development
- managing energy-related environmental and health impacts
- securing supply through diversity.

In 2007, due to the unforeseen high rate of economic growth and resulting change in policy direction, the Minister of Mineral and Energy, Bulelwa Sonjica, commenced a process to revise and update the 1998 white paper.

South Africa also has a white paper on renewable energy (Department of Minerals and Energy, 2003) which sets a 10-year target of 10,000 GWh to be derived from renewable sources by 2013. This policy is supplemented by two strategies directing government actions towards creating a more environmentally benign energy sector in South Africa: the renewable energy strategy and the energy efficiency strategy. The latter includes a target of 12 per cent reduction in energy use in 10 years.

## The application of S&T policy to natural-resource-based industries in South Africa

The S&T environment in South Africa is governed by the white paper on science and technology (Department of Science and Technology, 1996). The white paper introduces the concept of a national system of innovation, which represents the interactions of various institutions and policies through which the diverse aspects of science and technology are harnessed. By 1999 it was realized that the system was not making the desired impact in contexts where complex socio-economic challenges translated to limited S&T investment. The government then initiated sector-specific foresight studies whose analysis confirmed the need to approach innovation through sector strategies. This led to the development of the South African research and development strategy (Department of Science and Technology, 2002), which rests on three pillars:

- innovation
- science, engineering and technology human resources development and transformation
- creating an effective government science and technology system.

The innovation pillar involves the establishment and funding of a range of technology missions that are critical to promoting economic and social development. These include the two key technology platforms

of the modern age, namely biotechnology and information technology, as well as two additional missions of particular relevance to South Africa: technology for manufacturing and technology to leverage knowledge from, and add value to, natural resources sectors.

The resource-based industries technology mission was introduced mainly to address the “natural resource curse” in South Africa. The mission was seen as a vehicle to bring about R&D strategies and activities that would stimulate the development of highly technical expertise and supply industries in resource-based sectors. The energy and minerals sectors presented near-term opportunities, as these sectors were mature in the South African economy and could leapfrog to new innovation frontiers. Hydrogen and fuel-cell technologies, with their link to platinum and energy production, became the focus of the mission as a platform to add value to the country’s natural resources.

South Africa is globally recognized as being a leading supplier of a variety of minerals and mineral products that are exported to as many as 87 countries. Each year approximately 55 different minerals are produced from more than 700 mining facilities, with gold, platinum-group metals, coal and diamonds dominating exports and revenue earnings. Most countries with natural resource wealth, like South Africa, have failed to translate resource-derived income into better livelihoods for their citizens. Numerous studies have found that countries lacking oil and mineral resources had much stronger GDP growth per capita than resource-rich countries (Ascher, 1999). These studies have shown that conducting innovation-based fiscal policy is extremely difficult for any country with high dependence on commodity exports. This “resource curse”, coupled with the crippling discriminatory policies of the apartheid regime, left the country with problems of large socio-economic inequalities that continue to be manifested in the form of high unemployment rates, wide areas of poverty and high levels of crime. The ability to create employment has been stifled to a great extent by policies that continue to encourage dependence on natural resources rent.

It is believed that once costs come down, hydrogen and fuel-cell technologies have the potential to revolutionize electricity supply options for remote rural areas. This would have a positive impact on economic development in rural communities that cannot be reached by the electricity grid. This is one of the key policy objectives of the South African energy white paper.

### *Precious metals resources development*

There are a number of government initiatives in South Africa aimed at stimulating downstream product development and manufacturing from

precious metals. Presently, platinum and other precious metals play crucial roles as catalysts that convert hydrogen to electricity. Platinum and its sister metals – palladium and rhodium, collectively called platinum-group metals (PGMs) – have unique characteristics that have driven technical and industrial advances in the fields of transport and energy. Catalytic converters containing PGMs, now fitted to some 90 per cent of new cars produced worldwide, have for example reduced emissions by 98 per cent in the European Union in the past 20 years, and could unlock the potential for a new clean energy source through their vital role in fuel-cell technology. The government plans to align this revolutionizing of the energy sector with the economic and developmental ambitions for South Africa, recognizing that the country needs to be involved in technology development and the manufacturing of products in order to benefit from the technology. The main demand sectors for platinum are currently jewellery (41 per cent), auto catalysts (41 per cent), electrical equipment manufacture (6 per cent), chemicals processing (5 per cent) and glass manufacture (5 per cent). The total demand has doubled in the last 20 years as new applications are found. South Africa has the largest platinum resources in the world (fig. 17.2).

At the moment, however, South Africa remains at the periphery of these PGM-related technological developments, as there is not enough knowledge generated locally to advance the downstream development

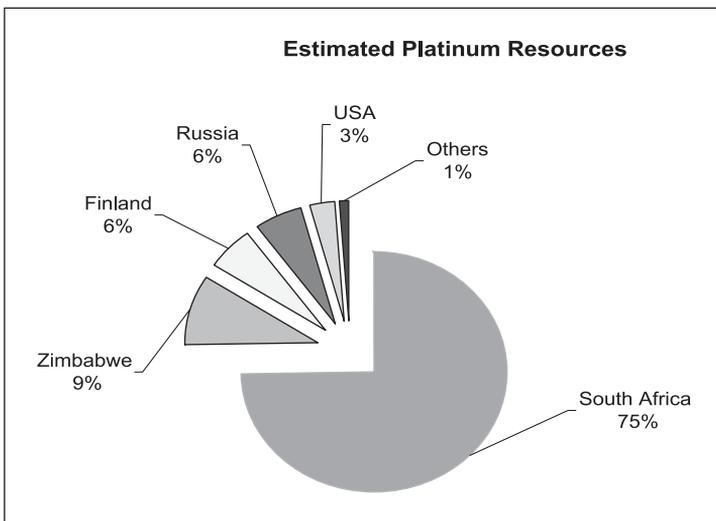


Figure 17.2 Estimated world platinum resources distribution

Source: Cawthorn (1999).

of products using PGMs. The emerging hydrogen economy presents opportunities for South Africa to build knowledge bridges and narrow the knowledge gap, as projections show that platinum will be the cornerstone of the hydrogen economy should suitable cheaper catalytic substitutes not be viable. South Africa plans to develop scenarios for an “industrial revolution” based on platinum resources for the global transition to hydrogen and fuel-cell technologies, rather than just capturing the markets for the raw material. This stems from the fact that different scenarios developed for fuel-cell cars over the next 50 years factor in South Africa’s ability to produce platinum in their sets of assumptions (UK Department for Transport, 2006).

The advent of a hydrogen economy would create a large new market for platinum-group metals that would be used as catalysts in fuel cells and fuel reformers. A marked increase in the demand for platinum in the automobile sector compared to other fuel-cell applications is expected, as Johnson Matthey’s 10-year projection illustrates (fig. 17.3).

According to General Motors, fuel-cell stacks for cars currently use about 2 oz of PGM per unit. Pure platinum catalysts are used for hydrogen-fuelled fuel cells, while alloys of platinum with ruthenium are typically used for reformed hydrocarbon fuels to improve the tolerance of the catalyst to carbon monoxide. The fuel-cell research team at Johnson Matthey believes that catalytic loadings can be reduced to about 1 oz by 2010 through better utilization of platinum and thinner deposition layers. The lowest laboratory data on platinum loading for efficient performance of fuel cells are currently about 0.8 oz (Borgwardt, 2001).

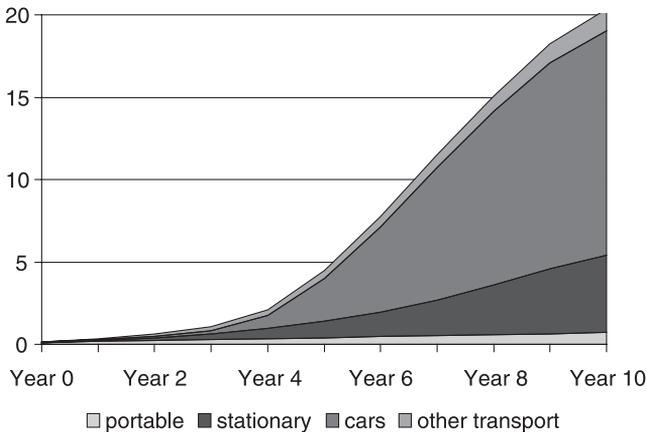


Figure 17.3 The role of platinum in future fuel-cell applications  
*Source:* International Platinum Association (2003).

It is projected that, with technology improvement, the platinum need per fuel-cell-driven vehicle would eventually be about 0.32 oz, compared to about 0.1 oz used in exhaust catalytic converters (International Platinum Association, 2003). Based on this estimate, for 10 million new cars per year (about 20 per cent of new cars produced) the consumption would be about 3.2 million oz, which is roughly half the current annual world platinum production. Selling at \$700/oz, this equates to a new market of about \$2.2 billion per year. But the price of platinum today hovers around \$1,300/oz, which almost doubles the revenue. This perpetuates the “resource curse” for a country like South Africa, where platinum mining companies enjoy revenues from the ever-rising commodity price. It becomes a challenge to motivate local downstream PGM development investments.

### *The pebble-bed modular reactor and coal gasification*

The pebble-bed modular reactor (PBMR) is a high-temperature reactor (HTR) with a closed-cycle gas-turbine power conversion system, and is currently under development in South Africa. Although it is not the only HTR being developed in the world, the South African project is internationally regarded as the leader in this field. Models have shown that the PBMR is capable of very high efficiency and attractive economics without compromising the high levels of passive safety expected of advanced nuclear designs (Ion et al., 2004). Developing out of a desire for energy sustainability, the PBMR technology defines twenty-first-century energy thinking.

The high process temperature in the PBMR can be harnessed for uses external to the reactor. High-value co-products, such as hydrogen from thermal electrolysis of water, desalinated water and industrial or residential process heat, not only set the PBMR-type reactor apart from all previous nuclear reactors but also make it an economical energy investment. The PBMR is therefore poised to be the world’s first commercial-scale process-heat-producing advanced reactor to be built in the new millennium.

Hydrogen remains one of the challenges facing the future hydrogen economy. Large amounts of energy are required to produce hydrogen. Providing high-temperature process heat for the generation of clean and carbon-free hydrogen could become South Africa’s near-term contribution to the global emerging hydrogen economy. Opportunities are also being explored for the use of process heat and hydrogen in other energy sources, such as coal gasification and oil sands. Enriching synthetic gas in coal-gasification processes with hydrogen would minimize the amount of CO<sub>2</sub> produced and result in increased product yields. These possibilities

open paths to a cleaner energy paradigm which could minimize the carbon footprint from coal-burning energy processes.

## Learning through inter-firm and North/South collaboration

Intelligent Energy, a Johannesburg-based subsidiary of the global energy solutions company Intelligent Energy, is particularly active among the companies engaged in fuel-cell demonstration projects. The pioneer of fuel cells in South Africa, in 2005 Intelligent Energy (IE) installed the first rural healthcare fuel-cell installation in Africa: a low-power fuel cell fuelled with bottled hydrogen powering a vaccine refrigerator in the Zanempilo clinic near Bisho. The demonstration project was set up in collaboration with South African partners Afrox, GF Louw and Minus 40, and partly funded by the Business Linkages Challenge Fund (BLCF) and the UK government's Department for International Development (DFID). The refrigerator is especially designed to run off a 12 V supply, and therefore IE developed a hybridized system where the refrigerator is grid-connected with battery and fuel-cell back-up. This means that failure of any one of these three power sources does not cut power to the refrigerator.

Before this installation, power shortages had meant that vaccines needed to be removed and stored in ice-boxes. However, when the power went down at night or over the weekend the vaccines would often be ruined. Also, before installing the 12 V refrigerator, the clinic was using a normal household refrigerator that was not ideal since temperature control was difficult. In summary, this clinic is an example of how fuel cells can provide back-up power for critical front-line healthcare equipment in developing countries.

In 2004 IE, with partners Afrox and Eskom, installed a large 2–4 kW combined heat and power fuel cell in the Bedford Gardens Hospital in Johannesburg. This was a learning-by-doing project. Hydrogen was supplied by Afrox in bottles; Eskom provided technical electrical know-how. The fuel cell was housed in a boiler room and the electrical load was utilized in the hospital canteen. This large fuel cell also produced hot water, which was used in the boiler room. Larger fuel cells of this size can provide back-up power for computers and lighting in urban hospitals, and in the future, after certification, power for critical equipment. In summary, a 2–4 kW CHP unit installed in an urban hospital demonstrated that IE's fuel cells can provide clean, reliable power as well as hot water.

IE has also installed a fuel cell for back-up power in a facility incorporating solar panels at Mkuze in KwaZulu-Natal. The Mkuze operation uses fuel cells, batteries, solar power and liquefied petroleum gas to

provide a complete energy solution for a community of thousands. The fuel cells are the back-up energy supply for computers that control the other energy sources. In Durban an IE fuel cell powers automatic water-level monitoring equipment which radios dam levels back to Durban Metro Water.

Other forms of collaboration such as licensing and distribution have been explored in South Africa. These offer limited experiential learning for the country, and should evolve to possible future local manufacturing opportunities. For example, IST Holdings is the Southern African licensee of Plug Power and imports its fuel-cell modules. IST is currently marketing off-the-shelf 5 kW PEM units and plans to launch solid oxide fuel cells (SOFCs) using liquefied petroleum gas and with a reformer unit for continuous power supply. IST is also strongly involved in the development of the PBMR technology and has an interest in thermo-chemical hydrogen generation using nuclear energy.

In December 2005 the International Finance Corporation, the private sector arm of the World Bank, awarded a US\$3 million (about R18 million) grant to IST and Plug Power to install 400 fuel cells in remote locations and cities of South Africa over the next three years. According to Plug Power the project, worth a total of \$14 million (about R85 million), will represent the largest number of commercial fuel cells to be installed in a developing country to date.

## Research at higher institutions of learning and science councils

Several of South Africa's universities and science councils are already engaged in research on fuel-cell technologies. Three of these stand out in particular.

The University of the Western Cape houses the South African Institute for Advanced Materials Chemistry (SAIAMC). The aim of this group is to commercialize the membrane electrode assembly (MEA) and develop a direct-methanol fuel cell (DMFC) as well as hydrogen generation prototypes. The group has been involved in fuel-cell and hydrogen generation RD&D for the last five years and holds seven local and international patents relating to these investigations. In the development of DMFC stack components, recent research has focused on developing platinum-group nanophase electrocatalysts, catalytic inks and proton-conductive membranes. Novel low-cost inorganic proton-conducting membrane materials are also developed to overcome the limitations of the current Nafion polymer-based membranes, which suffer from draw-

backs such as high cost, poor temperature resistance, low durability and high permeability, resulting in inefficiencies. This research effort includes innovative gas diffusion layers, MEAs and fuel-cell stack designs, with prototyping and demonstration opportunities being sought.

In R&D for hydrogen production, the group is developing nanostructured and composite low-cost electrodes for alkaline flow cells as well as solid-state electrolyzers based on reverse-fuel-cell systems. This also requires the development of suitable precious metal nanophase electrocatalysts and composite catalytic electrodes for such hydrogen generation systems. These activities involve innovation in catalytic inks, MEAs, gas diffusion layers and cell designs with prototyping. Novel secondary structured metallic as well as composite electrodes prepared with Pt-based nanophase electrocatalysts supported on mesoporous materials have already been fabricated, and are much more active for hydrogen generation than current commercial materials for each system. The group has also started on R&D for hydrogen hydride storage.

The Catalysis Research Unit in the Chemical Engineering Department of the University of Cape Town is involved with R&D in fuel-processor catalysts, principally for hydrogen purification. Its facilities include modern laboratories for preparation, characterization and testing of catalysts. Cross-cutting R&D activities that may be relevant to the emerging fuel-cell industry technologies are nanoparticulate catalysts of active materials and chemical catalysis.

The University of Limpopo specializes in computational modelling and has investigated modelling of O<sub>2</sub> diffusion in solid oxide FC electrolytes such as cubic ZrO<sub>2</sub>. It has recently embarked on the modelling of water in Nafion to increase operating temperatures of composites to retard poisoning of Pt catalysts in fuel cells. The team has at its disposal sophisticated computational modelling computers and software to support the work. It has published about 15 papers on fuel cells and energy storage in recent years.

In addition, there are more than 10 universities and over 15 universities of technology in South Africa involved in R&D programmes that could provide input to a coordinated hydrogen and fuel-cell technologies effort. The new South African strategy aims to draw on all these existing capabilities and create a coordinated development programme.

Mintek, one of the government's research laboratories, is a leading provider of minerals processing and metallurgical engineering products and services in South Africa. The group is involved in catalysis synthesis processes, catalysis characterization, test-beds and MEA research. The Centre for Scientific and Industrial Research (CSIR) is South Africa's largest science and technology research organization, although its research in fuel-cell technologies has been rather limited. Over the past

few years, however, the organization has devised strategies to develop expertise in the area of hydrogen and fuel-cell technologies.

### The national hydrogen and fuel-cell technologies research, development and innovation strategy

Through its collaborative linkages with enterprises in the North and its university- and science-council-based research activities, South Africa is in the process of implementing a double-sided research agenda to support the national hydrogen vision. One side supports the building of appropriate local manufacturing skills by encouraging the licensing of foreign technology and stimulating the local manufacture of systems to address current energy supply and delivery challenges. The other side generates the scientific knowledge to develop new, more cost-effective, hydrogen and fuel-cell technologies for niche applications. The newly adopted national hydrogen and fuel-cell technologies research, development and innovation strategy aims to guide the process to strengthen the knowledge base.

The rationale for South Africa's involvement in the development of this technology is matrixed in a complex web of drivers. South Africa cannot ignore global energy challenges, such as security of supply, decreasing oil reserves and environmental concerns, and it needs to give access to modern energy services to all its citizens. South Africa realizes that hydrogen and fuel-cell technologies will develop regardless of whether it participates in these developments or not, even though the country will supply most of the catalytic input material. The revolution in telecommunications irreversibly changed the way the world communicates, and affected even those countries that chose not to invest in the knowledge needed to develop that industry. South Africa recognizes that if it does nothing about the emerging hydrogen and fuel-cell technologies, it will gain from such developments simply by being a customer deriving benefit from the use of these technologies and a major supplier of platinum for use as a catalyst.

However, the South African government desires to deal with some of its developmental challenges through stimulating innovation in the economy. The Department of Science and Technology (DST) has led the drive to increase the H&FC technology knowledge base in South Africa. In 2004 it commissioned a baseline study to investigate local and international developments related to H&FC technologies (Department of Science and Technology, 2005). In 2005 the DST hosted a high-level policy workshop where a number of international experts evaluated South Africa's comparative and competitive advantage in H&FC an; the

findings were presented to the cabinet, which approved the DST's plan to invest in the creation of a knowledge base for the future economy in which H&FC technologies play a significant role. A team of local and international experts was assembled to develop a strategic framework that will advance the creation of this knowledge base. The strategic framework was approved by the cabinet in May 2007, and it makes several high-level pronouncements (Department of Science and Technology, 2007).

### *Vision of the strategy*

The vision of the strategy is to create knowledge and human resource capacity that will develop high-value commercial activities in hydrogen and fuel-cell technologies utilizing local resources and existing know-how.

### *Strategic objectives*

The objectives of the strategy are informed by the need for knowledge generation, the availability of resources, both physical and natural, the need for economic development and participation in the global knowledge economy. These strategic objectives will be realized through focused investment in research infrastructure that will yield suitable and specialized human resources. Skilled people are required at all levels who will understand, innovate, develop and support technological activities. This strategy pays considerable attention to growing human capital, including attracting young researchers and cultivating a vibrant mentoring environment. A targeted human capital development programme will also ultimately influence the nature, direction and commercialization of H&FC R&D in South Africa.

The primary objectives of the strategy are discussed below.

### *Wealth creation through high-value-added manufacturing*

Economic development is a priority for South Africa, and a shift to high-value, knowledge-intensive products is a national objective. The investment in R&D has two objectives: commercialization of the resulting technology that will lead to increasing employment, exports and national wealth; and improvement in the quality of life of South Africans. This is in part linked to the world's largest PGM reserves being found in South Africa. Extensive R&D and knowledge generation are required; catalysis has been identified as one area in fuel-cell technologies that requires a substantial amount of fundamental scientific research. R&D will not only focus on technical matters but also on cost, life cycle and applications.

### *Developing hydrogen infrastructure solutions*

Large-scale production of hydrogen is key to a successful transition to H&FC technologies. To date the production of hydrogen remains one of the biggest challenges facing this nascent industry. The strategy will thus build on the existing knowledge in high-temperature gas-cooled nuclear reactors and coal-gasification Fischer-Tropsch technology to develop local cost-competitive hydrogen generation solutions. Focused R&D programmes will also seek to improve storage methods based on South Africa's natural resources.

### *Equity and inclusion*

The strategy is in part about creating a path for the economy as a whole to benefit from its natural resource endowment. The economic benefit from the country's large PGM resources has been limited by the lack of an appropriate manufacturing base. For the resource rent to reach the poor and marginalized part of the population, more employment opportunities have to be created. The long-term secondary benefits would be the supply of reliable energy. Fuel cells have the potential of providing reliable electricity and thermal energy. At current international prices, the technologies are still too expensive for poor people.

## Implementation of the H&FC strategy

The DST adopted three themes, and named them national research flagship projects under the hydrogen and fuel-cell technologies research, development and innovation strategy. The projects aim to increase scale and focus and bring together complementary expertise towards a common strategic research goal. They will be based on partnerships of leading South African scientists, research institutions, commercial companies and selected international partners. A hub-and-spoke collaborative model will be adopted for the implementation of the each flagship project. The three hubs have been established; the formation of the spokes will be through competitive calls following a thorough roadmapping exercise for each of the flagship areas.

In essence, this hub-and-spoke model is a mechanism to bring together high-level local and international experts to develop a long-term vision to address specific challenges in identified theme areas, create a coherent, dynamic strategy to achieve that vision and steer the implementation of an action plan to deliver agreed programmes of activities and optimize the benefits for South Africa.

### *National research flagship project topics*

- *Catalysis applicable to H&FC technologies.* The strategic goal is for South Africa to supply a share of the global fuel-cell market with novel PGM catalysts.
- *Hydrogen infrastructure.* Pursuing opportunities for using local resources to address technological challenges in hydrogen production, delivery and storage, and safety, codes and standards.
- *Systems analysis and technology validation.* The goal of this focus area is to establish common bases for analysing alternatives at the system, technology or component level in terms of cost, performance, benefit and risk impact.

### *Other programmes*

In addition to the national research flagship projects, several other activities will be undertaken.

- *Public awareness and acceptance.* The hydrogen economy will be a revolutionary change from the world we know today. Education of the general public, training personnel in the handling and maintenance of hydrogen system components, adoption of codes and standards and development of certified procedures and training manuals for fuel cells and safety will facilitate acceptance of hydrogen as a fuel.
- *Marketing and fostering strategic international partnerships.* The goal is to develop a programme of action to position South Africa as a significant partner in international consortia, using the 2010 Football World Cup to be hosted by South Africa to leverage these partnerships and address the clean energy challenge of the event and beyond.

## Conclusions

As a developing country with a significant natural resource endowment, South African economic growth is dependent on the ability of the economy to create optimal value from this endowment. Creation of such value in turn hinges on technological advancement and the ability of the country to develop the requisite scientific knowledge base that can translate global market opportunities into products and services. The progressive use of PGMs in automobiles, in both internal-combustion engines and fuel cells, is seen as an opportunity for South Africa to create a knowledge cluster around these resources.

As a global citizen, South Africa cannot ignore the global energy challenges. These challenges can only be addressed through technological advancement, and South Africa aims to be part of the global community that creates modern energy systems through advancement of scientific knowledge. South Africa is in the process of implementing its own strategy, which takes into account international developments while focusing on the country's strengths in resources and knowledge to carve out its future role in the emerging hydrogen economy.

Being a late entrant in the game, South Africa will leverage opportunities to learn from the developed countries by establish linkages for technology transfer and skills development, and creating opportunities for early adoption of technologies. The development of the South African strategy process was largely influenced by perspectives from international players, relayed through a group of international experts who were invited to review a draft strategy.

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## Dealing with a disruptive technology: Issues for developing countries

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*Lynn K. Mytelka*

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The future of the hydrogen economy is still an open question. Given the pressures upon governments, both North and South, to deal with environmental pollution and energy security in the longer term, can developing countries simply wait until a consensus process plays itself out in the North before taking their own decisions? Even more fundamentally, should the pace of change in the North set the trajectory in the South? The latter would be the logical outcome of the view that in developing countries “the introduction of fuel cell technology certainly will occur significantly later than in the industrialized countries because of cost and infrastructure issues” (Office of Technology Policy, 2003: 18). But should it?

### Dealing with pollution

There are a number of reasons why developing countries should be brought into the process of making choices and planning their transitions as quickly as possible, and why there will be a need for new sorts of partnerships to help bring this about. From a Northern perspective, perhaps the primary advantage of involving the South now is environmental.

Pollution reduction in the South is a win-win solution. The number of automobile and truck registrations is expected to increase substantially over the next 50 years, reaching 3.5 billion vehicles on the road by 2050, as compared with a 1996 figure of 670 million. Most of this increase will

be in developing countries, in which vehicle registrations are estimated to grow from under 100 million at the turn of the millennium to 2.5 billion by 2050 (Office of Technology Policy, 2003: 18). It is thus surprising that so little attention is being paid to opportunities for the development and diffusion of fuel-cell technology in these countries. Perhaps the only major programme currently under way is the testing of fuel-cell buses with the support of the Global Environment Facility (GEF).

Initially envisaged as a programme in five megacities with both serious pollution problems and a strong scientific and engineering base – Shanghai, New Delhi, São Paulo, Mexico City and Cairo – only three of these projects are fully operational today.<sup>1</sup> As chapter 8 pointed out, the high cost of the programme and the possibility of implementing alternative strategies, such as converting buses to CNG, constructing new forms of public transport in urban areas and the development of sustainable fuels such as ethanol and biodiesel, have been a disincentive to participation in this programme. But most developing countries are neither learning through such testing programmes nor are they aware of or able to implement the alternatives discussed in chapters 5, 6 and 13, a point returned to below.

## Diversity of needs

Across the South, needs are different and a standardized approach to a transition would hardly be appropriate. For oil producers in the South such as Nigeria, discussed in chapters 7 and 16, choices are framed by the likelihood that the emerging hydrogen economy will spell a significant drop in oil consumption<sup>2</sup> and revenues, potentially within 20 years. While this allows a period of time in which to develop alternative uses for fossil fuels, such alternatives will have to be identified and the research and production capabilities put in place over the next 10–15 years. Similarly, for developing countries that have become involved in assembling automobiles and producing parts and components, as in the Malaysian case described in chapter 12, the car of the future will require new skills and new knowledge.<sup>3</sup> Strengthening the local knowledge base, ensuring its flexibility, engaging more intensively in domestic demand-driven research and creating new sorts of knowledge networks and partnerships will be needed to make the transition less painful.

More broadly still, many developing countries are moving down an older technological path as they continue to build their vehicle-related infrastructure – the auto-repair services, fuel distribution networks, refuelling stations – around the internal-combustion engine and the consumption of gasoline. This is all the more serious as many developing countries

have become major importers of used cars, thus creating more incentive to strengthen a fossil-fuel-based system. Were this to continue, North and South would find themselves on divergent paths with an ever-wider technological divide between them. From the perspective of the South, how the North deals with environmental pollution has a strong bearing on its own opportunities for growth. These cannot simply be reduced to accommodate lower levels of pollution worldwide. Instead, that growth must be hitched to the development and diffusion of technologies associated with the hydrogen economy.

Yet the process of catching up in these new-wave technologies is significantly different from traditional, engineering-based industries of the past. In those earlier waves of technological change, catching up depended more upon deepening production capabilities, thereby ensuring that the clones, copies or OEM goods were, at the least, of similar quality and yet initially competitive because they were cheaper. In the initial phase of a catch-up process there was thus little need for domestic R&D. Adaptation and modification that led to productivity increases or capital stretching could largely take place within the firm and through the strengthening of engineering capabilities. The process of catching up in these industries was thus an incremental one, in terms of the kinds of knowledge bases that were needed, the sequential way in which they would be acquired and the gradual building up of the system that enabled the imported technologies to function optimally in their new environment.

In science-based, patent-intensive and systems-embedded new-wave technologies, however, the process of catching up differs from this traditional incremental process and its focus on single enterprises and building basic skills first. Tertiary education and research are needed from the outset, as they permit close monitoring of the changing technological frontier, enable the identification of opportunities for entry into new productive activities and provide the base for a more holistic, systems-oriented approach to policymaking for the transition. These new capabilities will have to be developed, as will the awareness that such a process is even necessary. In the absence of attention to capacity-building processes now, developing countries run the risk of exclusion in the future.

### The problem of exclusion<sup>4</sup>

Although most people date the emergence of new-wave technologies to the advent of the semiconductor, in many respects new information and communications technologies (ICTs) were initially a transitional technology, emerging within the paradigm of earlier mechanically based indus-

trial revolutions and only later incorporating the genes, proteins and particles at the nano level that are central to new-wave technologies. Their introduction into products and processes was gradual, modular and additive, as components of existing products were progressively transformed from mechanical to digital and new products were created by combining upgraded versions of existing components in novel ways.<sup>5</sup> They were only a foretaste of what might be in store.

Like mechanically based industries of the past, entry into the electronics industry was still possible at low skill levels, and most manufacturing activities located in the developing world required only semi-skilled labour. Although a conscious effort to learn was required, opportunities for catching up were present when industries matured slowly, product life cycles were longer and competition from lower-wage entrants was not yet intense. The need for domestic R&D in the early phase of the catch-up process in ICTs was also limited, and patent protection was not very important. This encouraged reverse engineering within the firm, and the adaptation and modification of imported technologies that made further learning and innovation possible.<sup>6</sup>

Although this new generic technology brought many benefits, as it transformed traditional information and telecommunications processes, led to the creation of knowledge-based products in a wide variety of different industries and stimulated the development of the internet, there emerged what has become known as the “digital divide”. From the outset the digital divide was defined mainly in infrastructure terms – access to telecommunications and computers. This, it was assumed, could be remedied by higher doses of technology transfer from North to South, notably through the extension of electricity generation and telecommunications switching and transmission equipment. The knowledge dimension and the way in which scarce knowledge resources affect the use and diffusion of new technologies were largely ignored. Since developing countries were widely regarded as users and not producers of the new ICTs, state-initiated efforts to master these technologies were criticized as inefficient and market distorting.<sup>7</sup> The “learning to learn” and the extensive knowledge accumulation and innovative capacities that such efforts could create were simply dismissed, and little attention was paid to the emergence of a “domestic digital divide” (Hibert and Katz, 2003: 63) that progressively excluded large numbers of potential users in education, research and business where reliance on computers and the internet was increasing (Oyelaran-Oyeyinka and Adeya, 2004; Oyelaran-Oyeyinka and Lal, 2006). Had developing countries been regarded not merely as passive technology users but as potential knowledge creators and innovators, and had a systems-oriented approach been taken from the outset, the problems of domestic content, costs and the development of the ancillary

educational, research, manufacturing and service activities needed to indigenize a learning and innovation process would probably have been resolved sooner and access widened more quickly. But this was not the case, and the digital divide is still very much with us.

Since the 1990s a second wave of technological change has transformed the development of new products and processes in ICTs and brought about the application of biotechnology to pharmaceuticals and agriculture. In these new-wave technologies, the knowledge dimension is now much more evident in the strong role that the science base plays and the intensity of patenting activity. The belief that development pathways of the past will be those trodden in the future must thus be tempered by this new reality. In a knowledge-based economy, the locus of knowledge creation and the forms through which knowledge is appropriated will increasingly shape opportunities for learning, for innovation and thus for growth and development.

As hydrogen fuel cells emerge as yet another disruptive technology, the role of the South as a “technology user” is becoming even more problematic and raises the spectre of cumulative and path-dependent growth in inequalities between North and South in the future. Catching up in these science-based, patent-intensive technologies, whether as users or producers, will require more attention to the development of tertiary education and public sector research capabilities, not only to widen the range of choice, reduce costs of final products and adapt these new technologies to local needs, but also to provide the basis for more informed policymaking processes.

## Strengthening tertiary education and public sector research

The 1980s and 1990s were years in which the contribution of public sector research institutes and universities to innovation, especially in the United States and a number of European countries, came under strong criticism and support for these knowledge-based organizations began to erode. It was no surprise, therefore, that faced with the austerity measures imposed as part of World Bank/IMF structural adjustment programmes in many developing countries, the budgets of these organizations were sharply cut.

In the current context, such strategies need to be rethought. Without a radical rebalancing of current educational practices to strengthen tertiary education and build networks among centres of research and training excellence, closing the knowledge gaps of the future will be even more difficult. While universities and research organizations are once again regarded as potential contributors in dealing with the challenges of growth

and development, simply returning to past practices in which reform of the science and technology sector focuses mainly on the supply of researchers and research outputs is not likely to solve the “innovation” problem, where innovation is understood as the application of new knowledge in production.

As research on new-wave technologies in developing countries has shown, pumping up the supply of science and technology outputs alone will not be enough.<sup>8</sup> The ability to use these new technologies and to adapt and apply them across all productive and service sectors will require not only more attention to the development of tertiary education and public sector research capabilities, but also new stimuli for both producers and users of knowledge – private sector firms, government ministries, innovation intermediaries, environmental services organizations, NGOs, regional and local organizations – to work more closely together.

To conceptualize the set of policies and programmes, the channels for knowledge and information flows and the financing mechanisms that sustain an innovation process, a more systems-oriented approach will be needed from the outset. Only in this way will technological change open opportunities for the development of a robust and competitive SME sector alongside the science- and engineering-based capabilities needed to adapt new-wave technologies to local needs. Thinking about transitions early in the process of a technological revolution thus has the potential to narrow gaps rather than widen them.

## Building capacity in hydrogen, fuel cells and HFCVs

A small number of developing countries with strong science and engineering capabilities have created teaching and research programmes in the chemical and electrochemical engineering and natural science bases that underlie the emerging hydrogen economy. These countries are also participating in a variety of networks through which they are able to learn about hydrogen, fuel cells and their applications in both transport and stationary power sectors, and monitor the frontiers of change in these fields. But this is not the case for the majority of developing countries.

What to learn and how to advance the learning process at home and diffuse such knowledge more widely require further reflection. Study tours by science, technology, energy and education ministries from interested developing countries should be organized to visit leading developed and developing country teaching and research institutes, with a view to building the knowledge about critical science and engineering inputs needed to design programmes at home. Study tours such as these

also help to create the knowledge networks that enable developing countries to access a continuous flow of new knowledge.

In a small number of developing countries, research programmes are already under way on hydrogen fuel cells for both stationary energy and transport, and on alternatives such as electric vehicles. Brazil, China and India are in the forefront of these activities, but South Africa and Malaysia are moving rapidly in this direction.<sup>9</sup>

While the creation of full-scale training programmes in the developing world will take considerable time, it would be possible now to establish networks of centres of excellence involving universities and research institutes in Africa, Asia and Latin America. These could be anchored by established research and training programmes in those countries of the South that have developed strengths in hydrogen, fuel cells and alternatives, and linkages could be established to partner institutes in the North. A number of international organizations are also now able to provide research support and learning and networking opportunities. UNIDO's ICHET, an international centre specialized in hydrogen and fuel cells, has an extensive pilot research programme under way on different methods to produce hydrogen from renewable energy sources such as solar, biomass and wind, as well as the use of hydrogen to power three-wheelers and buses. Argentina, Morocco, Algeria, Libya, India and China are involved in this project.

Collaborative research and testing programmes and the exchange of postgraduate students and confirmed researchers would in only a few years supply core staff for local research and training capabilities and provide support to government monitoring and policymaking activities. They would provide the basis, moreover, for an expansion of the country's absorptive capacity and thus enable local research and production to emerge more quickly.

## The development and use of fuel cells for stationary power

Hydrogen fuel cells are a dual-use technology and can be developed for both the transportation and the stationary power sectors. For fuel-cell manufacturers, such as Ballard Power Systems for example, maintaining a foot in both camps has been essential in growing the company. Ebara Ballard was thus there when Japan decided to move towards the development of co-generation plants in Tokyo.

Even though full-scale production of hydrogen fuel-cell cars for most companies will not take place much before 2020, dual-purpose usage of HFCs in stationary power systems and in a variety of fuel-cell vehicles such as forklifts is creating economies that should enable fuel-cell manu-

facturers to reach their break-even point of about 300,000 stacks per year without having to produce 300,000 FCVs a year. Economies of scale in the manufacture of automobiles might thus not be as much of a constraint as is currently the view.

Both PAFCs and PEMFCs have been installed widely in the United States, Japan and Europe since the mid-1990s,<sup>10</sup> and more recently in Canada, Korea, India, Brazil and China. This would be an opportune moment for other developing countries to study these technologies and build up a capacity to evaluate the conditions under which they operate well and at affordable costs. By building a more distributed form of energy generation, one that could operate by using biofuels and solar cells, some developing countries might thus avoid the environmentally damaging construction of hydroelectric dams and the high costs of building power grids that transmit energy with decreasing efficiency over long distances. However, leapfrogging over these earlier technologies and into the optimal use of a new-wave technology is not merely a question of “technology transfer” but involves a conscious effort at learning and capacity building across a broad range of scientific, engineering and social science disciplines.

## Learning through HFCV testing programmes

Over the past five years testing of newer types of fuel cells and stacks, as well as of a variety of fuel production, distribution and on-board storage systems, has progressed considerably in Europe, North America and Japan. Much of this was supported through public funds or involved public-private collaborations such as the California Fuel Cell Partnership, the Japan Hydrogen and Fuel Cell Park or the EU’s CUTE project. Experimental hydrogen refuelling stations have been set up in Japan, Iceland, the European Union<sup>11</sup> and California as part of programmes to road-test hydrogen-powered FCVs.<sup>12</sup> By 2005 fuel-cell bus testing, under way for several years in Canada, Europe and the United States, had been extended to a small number of developing countries.

Under the GEF of the UN Development Programme (UNDP), a project to deploy and test fuel-cell buses in five developing countries was adopted. The project, which would test up to 40–50 buses, was anticipated to cost approximately US\$130 million. The choice of countries, and within them of specific cities for testing the vehicles, reflects a dual consideration: the large, urban, highly polluting transport systems in cities such as Beijing, Shanghai, New Delhi, São Paulo, Mexico City and Cairo; and the strong engineering base needed to undertake these testing programmes and learn from them.

At present, the programme in China is furthest along and the Beijing demonstration project has already been completed. The Tata Energy Research Institute in India is currently testing a Ballard fuel-cell bus, but given the high cost of these buses, New Delhi, which only recently converted its bus fleet to CNG vehicles, has not begun a broader testing programme. The same is true in Cairo and Mexico City, which have adopted alternative programmes for the reduction of urban transport pollution.<sup>13</sup>

To diffuse knowledge across the developing world, countries in both North and South with ongoing fuel-cell bus and car testing facilities and a variety of different types of hydrogen refuelling stations might consider the formation of a consortium for knowledge production and sharing on the lessons learned from testing programmes. This could take a number of forms. Systematic comparative analysis across testing programmes could form the basis for an understanding of the strengths and weaknesses of various technologies and the social, economic and environmental conditions under which they work optimally. The lessons learned from testing can be incorporated into training manuals for researchers and policymakers from other developing countries. Such manuals would include information on the operating parameters within which testing is taking place, performance criteria and evaluation, techniques for learning and analysis, adaptive choices and changes in the course of testing programmes, and the impact of lessons learned on policies, programmes and future technological trajectories in countries conducting testing. The consortium could plan a series of training programmes on a country or regional basis to diffuse this information more widely. Consortium members could also open their facilities and programmes to visiting scholars for internship, training and collaborative research work.

## Evaluating alternatives and making informed choices

There is currently a wide range of alternatives for reducing pollution in the transport sector. Not all of these push the technological frontier forward or bring about more fundamental changes, but many enable countries to undertake changes that reduce pollution without moving them down trajectories that diverge from those at the forefront of the technological change process. However, there are currently no methodologies available that enable developing countries to evaluate these alternatives from a multi-goal, long-term perspective. Most methodologies continue to take a narrow problem-solving approach to pollution, such as simply using end-of-pipe solutions or transferring the centre of the problem from the final user to the source of energy. This may hide it briefly from

public view, but does little to change the overall environmental impact or the underlying consumption and production models that are generating the problem. It tends, moreover, to prolong the life cycle of earlier technologies when the moment to invest in newer, potentially more effective, efficient and sustainable technologies may have arrived.

There is also a problem in choosing among alternatives. The criteria that are used can tilt the balance in the choice of technologies to those that either bridge the move towards a technological revolution or become barriers to it. Policies have a particularly important role to play in this respect, as they shape the parameters within which choice-sets are established and criteria selected. In many countries, for example, policies have created incentives for the continued use of fossil fuels such as gasoline and natural gas, albeit with efforts to produce cleaner fuels and towards the development and purchase of hybrid vehicles that reduce overall pollution levels and create marginally greater fuel economies – as opposed to reshaping existing practices in the patterns of consumption and production that currently favour roads and personal vehicles over alternatives in the transport sector. This was the logic implicit in the approach to the choice of alternative fuels presented in a report prepared by Adnan Shihab-Eldin, director of research at OPEC, and presented to the Eighth International Energy Forum in Osaka, Japan, on 21–23 September 2002. The argument begins with the affirmation that world energy demand will continue to grow through 2020, especially in the transport sector, and enquires into the technologies that might be available to meet this demand. Oil and natural gas are finite but still very abundant, and relatively low additional costs would be needed to expand production and infrastructure of these two fuels.<sup>14</sup> These hydrocarbon-based fuels, along with bio-ethanol, also have mature technologies, but increasing output of the latter and of biodiesel, a newer technology available mainly for pilot projects and at high cost, is limited by land. Both, however, can use existing gas stations and conventional ICEs. Natural gas, on the other hand, competes with increasing demand for power plants. The sole difficulty with oil, when compared to the others, is its emissions problems; but cleaner fuels in the transport sector can deal with these. The report thus concludes that “cleaner fossil fuels will continue to dominate the power sector, as well as most other sectors, for decades to come, if not throughout this century” (Shihab-Eldin, 2002: 305).

Most efforts at evaluating alternatives take existing trends as given and inflate the costs or difficulties of reversing them. The preference of consumers for SUVs is one example. Few efforts at evaluation, moreover, place dynamic longer-term goals, such as learning, high up in their list of priorities. Yet for countries in the South learning is the key to future

growth and development. Developing countries will need to factor opportunities for learning and capacity building into the evaluation process so that they can widen their choices in the future.

Evaluating alternatives also requires attention to the direction of change. Setting off down a path that diverges over time from what becomes the main technological trajectory of the future can be very costly.<sup>15</sup> How to deal with this problem is of some concern to developing countries. What short-term approach, for example, should be taken to ensure that any natural gas infrastructure which might be built is compatible with hydrogen, and what might be learned by using natural gas-hydrogen blends in the short term in CNG vehicles where access to natural gas is cost-effective?<sup>16</sup>

A number of steps can be taken to facilitate the choice process. One is to put in place a system for monitoring the pace of change in fuel-cell technologies and analysing the factors affecting it. Most developing countries cannot afford to undertake such continuous monitoring and evaluation on their own. A small secretariat and extensive networking via the internet can solve the problem of timely data collection, but the analytical problem remains. More work needs to be done to develop methodologies for evaluating change and deriving from them an appreciation of the range of alternatives, the conditions under which they can be effectively implemented and the speed with which new technological trajectories are emerging that might displace these alternatives.

Moving towards CNG vehicles as a way to reduce urban pollution in the medium term is but one example. Are the conditions within which this choice can be effectively implemented already in place? CNG, for example, was available in New Delhi when the Supreme Court set the deadlines for conversion of the municipal bus fleet in that city, but the infrastructure was not sufficient to meet demand when so many vehicles were converted at the same time (Singh et al., 2001). From a learning and innovation perspective, the ability to replace imported conversion kits with locally developed and cheaper kits was a plus. In contrast, the pace at which CNG vehicles are being adopted in Tokyo, where refuelling stations are not readily available and CNG vehicles are more expensive than diesel vehicles, is extraordinarily slow (Yarime, 2002).

Going beyond a choice based on a single criterion, it is also important to take a number of other key factors into consideration in choosing among alternatives. Which way to move, how and when? How to make such choices, and how to ensure that they are “evidence-based”? In searching for answers to such questions it is not enough to focus on short-term considerations, like the speed with which a given solution can be implemented, without addressing medium- and long-term equity is-

sues. What, for example, will be the economic and social costs of conversion, and who will bear these costs? What kinds of capacities need to be built, and what provisions need to be made to ensure that the capacity-building process does not exclude segments of the population?

Policies, whether tacit or explicit, shape the parameters within which decisions about investment and innovation are taken. They inevitably impact on the direction of technological change. Policy timing and sequencing are crucial, and complementary policies to offset inequalities in the ability of actors to respond to market signals are often needed. Building the channels for a continuous dialogue among domestic stakeholders thus plays a critical role in securing the benefits of science and technology for all people. It is through such dialogues that awareness of a wider range of choices with regard to domestic research and technology trajectories can emerge and research programmes that include sustained innovation in the smallholder agricultural sector<sup>17</sup> and in small and medium-sized manufacturing and service sector firms can be developed. Research is also needed to analyse alternatives *in situ*, identify possible collaborative partnerships and structure these to ensure that learning and capacity building takes place.

## Notes

1. See chapter 8 in this volume for an analysis of why Egypt has postponed fuel-cell bus demonstrations.
2. Some estimates have placed this as high as 40 per cent, and a quick look at oil consumption in the United States, where the transport sector depends on petroleum for 95 per cent of its fuel and transport accounts for 67 per cent of petroleum use, would support such a dramatic drop in oil consumption if gasoline-fuelled FCs do not become the dominant design.
3. These issues are addressed in chapters 6–8, 11 and 12.
4. This section is drawn from Mytelka (2004).
5. In this the early ICT industry paralleled the technological trajectory that characterized the internal-combustion engine and its application in the auto industry. For details see chapter 1 in this volume.
6. Korea and Taiwan illustrated this process. See, for example, Kim (1997, 2004); Ernst, Ganiatsos and Mytelka (1998); Kim and Nelson (2000).
7. These criticisms were particularly directed at efforts to develop computers in Brazil and digital switches in Brazil and India. For a discussion of some of these debates see Tigre (1983); Görensson (1993); Mytelka (1999).
8. Brain drain is a classic instance of the effect of a single focus on the supply side, as opposed to a dual focus on strengthening both supply capacity and domestic demand for new technologies that builds the linkages between users and producers which stimulate an innovation process.
9. See chapters 15 and 17 in this volume.

10. The Energy Information Administration's *Natural Gas Monthly* of May 1994 listed the companies that were already operating fuel-cell stationary power systems using PAFCs. There were some 30 power companies in the United States, seven in Europe and several others which now would have had some 10 years' experience in operating such plants.
11. Under the EU's CUTE (Clean Urban Transport for Europe) project, hydrogen fuelling stations are being set up to deliver fuel to 30 fuel-cell buses that will operate in the nine participating European cities: Amsterdam, Barcelona, Hamburg, London, Luxemburg, Madrid, Porto, Stockholm and Stuttgart. DaimlerChrysler will supply the buses.
12. These are being carried out by the California Fuel Cell Partnership.
13. See chapter 8.
14. The following comparison is drawn from table 10 in Shihab-Eldin's report and the categories used there to compare these alternative fuels (Shihab-Eldin, 2002: 294).
15. See, for example, the way in which pressures to reduce potentially toxic mercury effluent within a very short timeframe led to the adoption of an intermediate technology by Japanese firms in the chlor-alkali industry and the reconversion, at high cost, to a more suitable technology when it appeared on the market only a few years later (Yarime, 2003).
16. See for example, a paper by a researcher from the Université de Québec's Hydrogen Research Institute (Bose, 2004).
17. See, for example, the choice between ethanol produced from sugar grown on large-scale plantations and biodiesel produced from non-edible oils on smallholder farms in chapter 6 in this volume.

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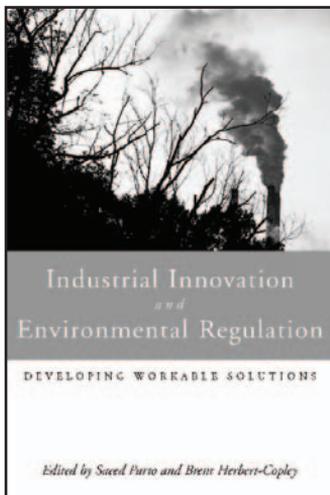
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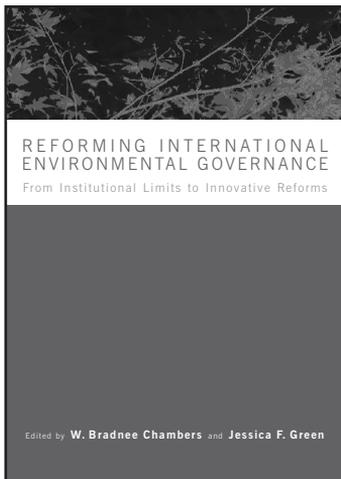
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