THE HYDROGEN ECONOMY

Opportunities and Challenges

In the light of ever-increasing global energy use, the increasing cost of energy services, concerns over energy supply security, climate change and local air pollution, this book centres on the question of how growing energy demand for transport can be met in the long term. Given the sustained interest in and controversial discussions on the prospects of hydrogen, this book highlights the opportunities and challenges of introducing hydrogen as an alternative fuel in the transport sector from an economic, technical and environmental point of view. Through its multi-disciplinary approach, the book provides a broad range of researchers, decision makers and policy makers with a solid and wide-ranging knowledge base concerning the hydrogen economy. The geographical scope of the book is global.

The Hydrogen Economy: Opportunities and Challenges is the first book to cover hydrogen in a holistic manner from a technical, environmental and socioeconomic perspective. Particular highlights include:

- Assessment of the benefits and downsides of hydrogen compared with other alternative fuels;
- Strategies and scenarios for a hydrogen infrastructure build-up;
- Interactions between hydrogen production and the electricity sector;
- Long-term global hydrogen supply scenarios and their impact on resource availability;
- The potential of hydrogen for decarbonising the transport sector;
- Macroeconomic impacts of introducing hydrogen as alternative fuel.

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Reviews of this book

'The world is facing a severe energy and environmental challenge, a challenge that is particularly acute for Europe – how to secure competitive and clean energy for its citizens against a backdrop of climate change, escalating global energy demand and future supply uncertainties. Hydrogen and fuel cell technologies have the potential to play a significant role in the development of a low-carbon, high efficiency energy system in Europe. This multidisciplinary book significantly broadens the perspective on the prospects of hydrogen as a universal energy vector and fuel, and provides a very important addition to the policy debate over future sources of transportation energy and the role hydrogen can play herein for the decades to come.'

Herbert Kohler, Chair of the European Hydrogen and Fuel Cell Technology Platform

'Sustainability of energy is one of the most important subjects in today's world. Our civilisation still relies almost entirely on fossil fuels to cover its energy needs. Their use has caused harmful consequences for the environment, from air pollution to global warming and climate change. What's more, fossil fuels are being depleted fast, with oil ranking first. All this should lead us to a transition away from today's petrol-based paradigm towards cleaner and ultimately renewable fuels. In this context, hydrogen is an ideal energy carrier: clean, efficient and safe, and as a synthetic fuel that can be produced from any primary energy source, it has the potential to address most energy needs of a sustainable transport system. In this book, the authors have carefully outlined the possible energy dilemma that could occur in the near future, and the particular challenges of the transport sector. The book is an important contribution to the discussion about the role of hydrogen in the future energy system, and should be of great interest to a broad readership, from policy makers to the general public.'

Mustafa Hatipoglu, Managing Director of the International Centre for Hydrogen Energy Technologies of the United Nations Industrial Development Organization (UNIDO-ICHET)

'The price of petroleum is rising continuously, as oil resources are being depleted fast. This is followed by price increases in natural gas and coal. In the meantime, the effects of global warming – such as stronger typhoons, floods and droughts – are becoming more prominent and destructive. The total cost of environmental damage last year alone is estimated to be six trillion dollars worldwide. The hydrogen economy is the permanent solution to these intertwined problems. *The Hydrogen Economy: Opportunities and Challenges* is a timely book outlining the opportunities presented by the hydrogen economy, as well as the challenges posed. I strongly recommend this excellent book to energy engineers, environmentalists and decision makers, as well as those interested in the future of humankind and the welfare of planet Earth.'

T. Nejat Veziroglu, President of the International Association for Hydrogen Energy (IAHE)

'Europe has the unique opportunity to lead the world and to create a low carbon energy economy, by boosting the development and deployment of cleaner and more efficient energy technologies. Hydrogen and fuel-cell-based energy systems hold great promise for achieving this vision. This book helps to understand the options around future mobility and stands out by its holistic approach in critically addressing the prospects of hydrogen in the transport sector from a technical, environmental and socioeconomic perspective. This book should be read by anyone involved in shaping the mobility mix of the future.'

Gijs van Breda Vriesman, Chair of the Governing Board of the European Joint Technology Initiative on Fuel Cells and Hydrogen

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On n'hérite pas de la terre de nos parents, on ne fait que l'emprunter à nos enfants.

Antoine de Saint-Exupéry

There are risks and costs to a programme of action, but they are far less than the long-range risks and costs of comfortable inaction.

John F. Kennedy

Contents

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Preface

The world is facing a severe energy and environmental challenge – how to provide competitive and clean energy for its citizens in light of an escalating global energy demand, concerns over energy supply security, climate change and local air pollution. More specifically, with soaring crude oil prices and with conventional oil becoming harder to find and produce, and its production eventually declining, there is a growing imperative to develop alternative fuels. At the same time, governments are stepping up their efforts to address the challenges of sustainable mobility and to foster the expansion of low-carbon fuels. Against this backdrop, this book centres around the question on how the growing energy demand for transport services can be met in the long term, while adhering to the aforementioned external framework conditions.

While the road-transport sector is expected to witness a much broader portfolio of fuels in the future, the context for considering alternative fuels is dynamic and uncertain. However, there is a growing consensus that electric mobility (i.e., whereby the vehicle drive is provided by an electric motor) is going to play a significant role in transforming the transport sector and could experience a substantial uptake in the future. Under such a scenario, hydrogen-powered vehicles could capture a noticeable market share. Hydrogen is particularly promising as it has the potential to address simultaneously all the major energy policy objectives in the transport sector, i.e., greenhouse-gas emissions reduction, energy security and reduction of local air pollution.

We have been involved in various hydrogen-related R&D projects, most notably aiming at developing strategies and roadmaps for the introduction of hydrogen in the transport sector. Given the sustained interest and controversial discussion on the prospects of hydrogen, this book intends to highlight not only the opportunities, but also the challenges of introducing hydrogen as an alternative fuel in the transport sector. The possible transition to a largely hydrogen-based transport system is placed in the context of the development of the global energy scene in the coming decades and analysed in a holistic manner from a technical, environmental and economic perspective.

Avoiding excessive technical jargon and technological details, the book aims to be of interest to a fairly broad readership (academia, policy makers and industry, as well as the interested reader) and to provide decision makers – through its multi-disciplinary approach – with a comprehensive and up-to-date reference and knowledge base about hydrogen. We hope that this book will broaden the perspective on the prospects of hydrogen as a universal energy vector and fuel, and that it will contribute positively to the policy debate over future sources of transportation energy and the role hydrogen can play herein for the decades to come. Areas covered include, among others:

- The benefits and downsides of hydrogen compared with other alternative fuels;
- Strategies and scenarios for a hydrogen infrastructure build-up;
- Interactions between hydrogen production and the electricity sector;
- Long-term global hydrogen-supply scenarios and their impact on resource availability;
- The potential of hydrogen for decarbonising the transport sector; and
- Macroeconomic impacts of introducing hydrogen.

While hydrogen and fuel-cell technologies are progressing, there is also continuing technical progress in a variety of other alternative fuels and efficient vehicle technologies, such as hybrid, plug-in hybrid, and pure electric vehicles, and liquid biofuels. In this respect, hydrogen should be seen as one option available in a broad move towards a lower-carbon energy system.

This book does not intend to pretend that hydrogen will solve all of our energy and environmental problems; nor does it intend to make forecasts about how the energy system in general and the transport sector in particular will evolve in the coming decades. Rather, this book is about presenting the choices at hand. In this sense, it strives to reflect critically on the various alternatives and strategies available to respond to the global energy challenge, in particular how to secure sustainable energy for transportation, as one of the pillars of our globalised world. Hydrogen and fuel-cell technologies are certainly very well positioned to become a major part of the solution.

For a long time, hydrogen has been the fuel of the future. The coming decade will be critical to prove the commercial viability of hydrogen and fuel-cell technologies. It will be interesting to look back in 20 or 30 years time to see how the *Future of Hydrogen* will have unfolded.

Michael Ball and Martin Wietschel
Stepanakert and Karlsruhe

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Abbreviations

ABM	Agent-based models
ACEA	European Automobile Manufacturers' Association
AFC	Alkaline fuel cell
AFS	Alternative fuel standard
APEC	Asia-Pacific Economic Cooperation
API	American Petroleum Institute
APU	Auxiliary power unit
AR4	IPCC Fourth Assessment Report
ASPO	Association for the Study of Peak Oil
ATR	Autothermal reforming
Balmorel	Baltic Model of Regional Energy Market Liberalisation
BAU	Business as usual
BCO	Bio crude oil
BEV	Battery-electric vehicle
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
boe	Barrel of oil equivalent
BTL	Biomass-to-liquids
BTU	British thermal unit
BWR	Boiling-water reactor
CAES	Compressed-air energy storage
CAFE	Corporate average fuel economy
CARB	California Air Resources Board
CBM	Coal-bed methane
CCGT	Combined cycle gas turbine
CCS	Carbon/carbon dioxide capture and storage
CDM	Clean development mechanism
CFC	Chlorofluorocarbon
CGE	Computable general equilibrium
CGH_2	Compressed gaseous hydrogen
CHP	Combined heat and power

cif	Cost, insurance, freight
CIS	Commonwealth of Independent States
CMG	Compressed methane gas
CMM	Coal-mine methane
CNG	Compressed natural gas
CONCAWE	The Oil Companies' European Association for Environment, Health and Safety in Refining and Distribution
COP	Conference of the Parties
cP	centipoise
CRW	Combustibles, renewables and waste
CSM	Coal-seam methane
CTL	Coal-to-liquids
DCL	Direct coal liquefaction
DDGS	Distillers dried grains with solubles
DEFC	Direct ethanol fuel cell
DICI	Direct-injection compression ignition
DISI	Direct-injection spark ignition
DME	Dimethylether
DMFC	Direct methanol fuel cell
DOE	Department of Energy (USA)
DP	Dynamic programming
DPF	Diesel particulate filter
ECBM	Enhanced coal-bed methane
EGR	Enhanced gas recovery
EIA	Energy Information Administration (US DOE)
EOR	Enhanced oil recovery
EPR	European Pressurised Water Reactor; Evolutionary Power Reactor
EROEI	Energy returned on energy invested
ETBE	Ethyl tertiary butyl ether
ETS	Emission trading scheme
EU	European Union
EUCAR	European Council for Automotive Research and Development
EUR	Estimated ultimate recovery
FAME	Fatty acid methyl ester
FAO	Food and Agriculture Organization of the United Nations
FBR	Fast-breeder reactor
FC	Fuel cell
FCV	Fuel-cell vehicle
FFV	Flexible-fuel vehicle
FOB	Free on board
FPFC	Fuel-processor fuel cell

FSU	Former Soviet Union
FT	Fischer–Tropsch
GAMS	General Algebraic Modeling System
GDP	Gross domestic product
GH_2	Gaseous hydrogen
GHG	Greenhouse gas
GIS	Geographical information system
GTL	Gas-to-liquids
GWP	Global-warming potential
HDV	Heavy-duty vehicle
HEV	Hybrid-electric vehicle
HFC	Hydrofluorocarbons
HFP	Hydrogen and Fuel Cell Technology Platform
HHV	Higher heating value
HOV	Highly occupied vehicle
HVDC	High-voltage direct current
IAEA	International Atomic Energy Agency
ICE	Internal-combustion engine
ICL	Indirect coal liquefaction
IEA	International Energy Agency
IEF	International Energy Forum
IET	International emissions trading
IGCC	Integrated-coal gasification combined-cycle
IMF	International Monetary Fund
IO	Input–output
IOC	International Oil Company
IPCC	Intergovernmental Panel on Climate Change
IR	Inferred resources
ITER	International Thermonuclear Experimental Reactor
JI	Joint implementation
JODI	Joint Oil Data Initiative
JRC	Joint Research Centre
LCA	Life cycle analysis
LCFS	Low Carbon Fuel Standard
LDV	Light-duty vehicle
LEV	Low-emission vehicle
lge	Litre of gasoline equivalent
LH_2	Liquid hydrogen
LHV	Lower heating value
LNG	Liquefied natural gas

LP	Linear programming
LPG	Liquefied petroleum gas
LULUCF	Land use, land use change, and forestry
MCFC	Molten-carbonate fuel cell
mD	millidarcy
MEA	Membrane electrode assembly; Mono-ethanolamine
MFC	Microbial fuel cell
MMV	Measurement, monitoring and verification
MOREHyS	Model for Optimisation of Regional Hydrogen Supply
MOx	Mixed oxide
mpgge	Miles per gallon gasoline equivalent
MTBE	Methyl tertiary butyl ether
MTG	Methanol-to-gasoline
MTO	Methanol-to-olefins
NAFTA	North American Free Trade Agreement
n.a.	Not available
NEA	Nuclear Energy Agency
NEDC	New European Driving Cycle
NG	Natural gas
NGC	Natural gas from coal
NGL	Natural-gas liquids
NGPL	Natural gas plant liquids
NMVOC	Non-methane volatile organic carbons
NOC	National Oil Company
NUTS	Nomenclature of Territorial Units for Statistics
OGJ	Oil & Gas Journal
OLADE	Latin American Energy Organization
OECD	Organisation for Economic Cooperation and Development
OPEC	Organization of Petroleum Exporting Countries
OSPAR	Oslo Paris Commission for the Protection of the Marine Environment of the North East Atlantic
PAFC	Phosphoric-acid fuel cell
PEMFC	Proton-exchange-membrane fuel cell; Polymer-electrolyte membrane
PFC	Perfluorocarbons
PGM	Platinum-group metals
PHEV	Plug-in hybrid-electric vehicle
PISI	Port-injection spark ignition
PM	Particulate matter
POX	Partial oxidation
ppm	Parts per million
PPP	Purchasing power parity

PSA	Pressure-swing adsorption
PV	Photovoltaic
PWR	Pressurised water reactor
R&D	Research and development
RAR	Reasonably assured resources
RCS	Regulations, codes and standards
RD&D	Research, development and demonstration
RES	Renewable energy sources
RES-E	Renewable energy sources for electricity generation
RME	Rapeseed methyl ester
SCO	Synthetic crude oil
SCPC	Super-critical pulverised coal
SD	System dynamics
SEC	US Securities and Exchange Commission
SMR	Steam methane reformer
SNG	Synthetic natural gas
SOFC	Solid-oxide fuel cell
SPE	Society of Petroleum Engineers
SRES	IPCC Special Report on Emissions Scenarios
SULEV	Super-ultra-low-emission vehicle
SUV	Sport utility vehicle
TAR	IPCC Third Assessment Report
tce	Tons of coal equivalent
TDM	Transport demand management
toe	Tons of oil equivalent
TPES	Total primary energy supply
TSA	Temperature swing adsorption
TTW	Tank-to-wheel
UCG	Underground-coal gasification
UCTE	Union for the Coordination of Transmission of Electricity
ULEV	Ultra-low-emission vehicle
UN	United Nations
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFC	United Nations Framework Classification
UNFCCC	United Nations Framework Convention on Climate Change
UNSD	United Nations Statistics Division
URR	Ultimate recoverable resources
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

VOC	Volatile organic compounds
vol.%	Per cent by volume
WEC	World Energy Council
WEO	World Energy Outlook
WNA	World Nuclear Association
WRI	World Resources Institute
WTT	Well-to-tank
WTW	Well-to-wheel
wt.%	Per cent by weight
XTL	X-to-liquids
ZEV	Zero-emission vehicle