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978-0-521-88216-3 - The Hydrogen Economy: Opportunities and Challenges

Edited by Michael Ball and Martin Wietschel

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## 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.

MICHAEL BALL studied Industrial Engineering at the University of Karlsruhe, where he also received his Ph.D. in 2006 in the field of energy-system modelling, developing a model for hydrogen infrastructure analysis, which served as a tool for producing the European Hydrogen Energy Roadmap. After a stay as a researcher at the Fraunhofer Institute for Systems and Innovation Research (ISI) in Karlsruhe, he joined Shell in the Netherlands in 2006 as project CO<sub>2</sub> advisor.

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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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# THE HYDROGEN ECONOMY

## Opportunities and Challenges

Edited by

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CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press  
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

[www.cambridge.org](http://www.cambridge.org)

Information on this title: [www.cambridge.org/9780521882163](http://www.cambridge.org/9780521882163)

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First published 2009

Printed in the United Kingdom at the University Press, Cambridge

*A catalogue record for this publication is available from the British Library*

*Library of Congress Cataloging-in-Publication Data*

The hydrogen economy : opportunities and challenges / edited by Michael Ball, Martin Wietschel.  
p. cm.

Includes bibliographical references.

ISBN 978-0-521-88216-3 (hardcopy)

1. Hydrogen as fuel. 2. Hydrogen—Research—Economic aspects. 3. Hydrogen industry.
4. Alternative fuel vehicles. I. Ball, Michael. II. Wietschel, Martin, 1962– III. Title.

TP359.H8H858 2009

665.8'1—dc22

2009010742

ISBN 978-0-521-88216-3 hardback

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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*

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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.

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*Preface*

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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## Acknowledgements

This book being an edited volume, we would like to thank again all the lead authors and various co-authors for their valuable contributions, discussions and critical feedback.

We thank our editor Matt Lloyd at Cambridge University Press for his positive feedback and support from the first time he read the book synopsis. We also thank Diya Gupta, Anna-Marie Lovett and Alison Lees, who took us through the final stages of editing and production.

Last but not least, we would like to thank our families for their support and the time they gave us, which have allowed the realisation of this book. A special thanks goes to Ainhua for her enduring patience and support during the writing of this book as well as for the critical reading and editing of parts of the manuscript.



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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 <sub>2</sub> | Compressed gaseous hydrogen   |
| CHP              | Combined heat and power   |

*List of abbreviations*

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|         |   |
|---------|---|
| 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 <sub>2</sub> | 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 <sub>2</sub> | Liquid hydrogen                                  |
| LHV             | Lower heating value                              |
| LNG             | Liquefied natural gas                            |

*List of abbreviations*

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|         |   |
|---------|---|
| 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                           |

Cambridge University Press

978-0-521-88216-3 - The Hydrogen Economy: Opportunities and Challenges

Edited by Michael Ball and Martin Wietschel

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|        |                            |
|--------|----------------------------|
| 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      |