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Scope of the book

Michael Ball and Martin Wietschel

Already in 1874, Jules Verne, in his novel *The Mysterious Island*, lets the engineer Cyrus Harding reply when asked what mankind will burn instead of coal, once it has been depleted:

> water decomposed into its primitive elements, . . . and decomposed doubtless, by electricity . . . Yes, my friends, I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.

Today's energy and transport system, which is based mainly on fossil fuels, can in no way be evaluated as sustainable. In the light of the projected increase of global energy demand, concerns over energy supply security, climate change, local air pollution and increasing prices of energy services are having a growing impact on policy making throughout the world.

At present, oil, with a share of more than one third in the global primary energy mix, is still the largest primary fuel and covers more than 95% of the energy demand in the transport sector. With continued growth of the world's population and industrialisation of developing nations, such as China and India, accompanied by an increasing 'automobilisation', a surge in global demand for oil is expected for the future. A growing anxiety about the economic and geopolitical implications of possible shortcomings in the supply of oil as a pillar of our globalised world based on transportation is increasingly triggering the search for alternative fuels. However, this search is not only motivated by possible oil shortcomings, but also in response to the climate change issue, because worldwide CO_2 emissions from the transport sector have been growing for decades and most projections show a further increase for the future.

At the heart of the book stands the question of how the growing energy demand in the transport sector can be met in the long term, when conventional (easy) oil will be running out. Among the principal options are unconventional oil from oil sands or oil shale, synthetic Fischer–Tropsch fuels on the basis of gas or coal, biofuels,

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electricity as 'fuel' for fully or partially battery-powered electric vehicles, and hydrogen. Unconventionals have a huge potential, but their extraction is very energy intensive and bears higher environmental impacts than conventional production. Synthetic liquid fuels from fossil energy sources can rely on the existing distribution infrastructure, but also come with a higher environmental footprint; moreover, from an energy-efficiency point of view, the syngas route is more favourable for the production of hydrogen than for Fischer–Tropsch fuels (neglecting infrastructure build-up and vehicle availability). 'Sustainable' biofuels increasingly face resource constraints and growing competition with electricity and heat generation, as well as with food production. Electric mobility on the basis of battery electric vehicles is, apparently, the most energy-efficient solution, but major technical and economic breakthroughs for vehicle batteries have to be realised first to bring this path into the market.

The need to modify the present trend, characterised by the unsustainable development of energy systems, requires that effective solutions are found and widely applied. Hydrogen is increasingly seen as offering a range of benefits with respect to being a clean energy carrier (if produced by 'clean' sources), which are receiving ever greater attention as policy priorities. Creating a large market for hydrogen as an energy vector offers effective solutions to both the aspects of emission control and the security of energy supply: hydrogen is emission-free at the point of final use, it is a secondary energy carrier that can be obtained from any primary energy source and it can be utilised in different applications (mobile, stationary and portable).

While the emergence of the so-called 'hydrogen economy', where hydrogen plays a major role as energy vector in the energy system, has been forecast by a range of experts from industry, policy and research and less-than-experts alike, for a number of decades, the discussion about hydrogen as future energy carrier or fuel has only in recent years been increasingly taken up by relevant stakeholders in the field, not least because of breakthroughs in fuel cell technology in the last decade. Despite the attention that hydrogen is receiving, in particular from policy makers and research communities, there is still a lack of publicly available literature about hydrogen for a broader expert group that covers all relevant topics. This book aims to close this gap and provide a synthesis of the latest, most important and interesting research findings and facts regarding the possible transition to a hydrogen-based energy and transport system.

The book intends to highlight both the opportunities and the challenges of introducing hydrogen as a potential energy vector from an economic, technical and environmental point of view. The focus is on the use of hydrogen as alternative fuel in the transport sector, which is generally considered the major driver for its introduction. Given the current controversy and popularity of the hydrogen issue, the book aims to provide – through its multidisciplinary approach – a broad range of decision makers (policy makers, academia, industry) as well as the interested reader with a solid and comprehensive knowledge base about hydrogen. The analysis focuses primarily on the time horizon until 2030. The geographic scope of the book is global, with the exception of a few chapters that are confined to a more European perspective.

The book at hand is the first book to cover hydrogen in a holistic manner from a technical, environmental and economic perspective. Particular highlights include:

- Assessment of the virtues and downsides of hydrogen compared with other alternative fuels in the transport sector;
- Strategies and scenarios for a hydrogen infrastructure build-up;
- Long-term global hydrogen supply scenarios and their impact on resource availability and contribution to CO_2-emissions reduction in the transport sector; and
- Macroeconomic impacts of introducing hydrogen as alternative fuel.

The book is organised as follows.

Chapter 2 addresses why hydrogen has recently been receiving increased attention. First, the challenges of today's energy system – security of supply and reduction of greenhouse-gas emissions – are discussed and existing and emerging energy policies to cope with them addressed. This sets the scene for the introduction of hydrogen, which needs to be seen in the context of the development of the global energy scene. The possible emergence of a hydrogen economy is then reflected from the perspective of historical transitions of energy sources. Next, the chapter outlines which are the major drivers for the possible transition to a hydrogen economy and what potential benefits could be expected from using hydrogen as an energy vector.

One major driver for hydrogen is concern about energy supply security due to shortcomings in the supply of fossil fuels, particularly oil. This aspect is dealt with in Chapter 3. First, the development of the past and present global energy supply are briefly analysed. The focus is on the development of oil and natural-gas production and consumption, as these fuels are expected to be most sensitive with respect to resource-economic constraints in the coming decades. Regarding the remaining reserves of oil and gas, both the 'pessimistic' and the 'optimistic' views are discussed. A special emphasis is placed on the potential availability of unconventional oil and gas deposits and the possible implications resulting from their extraction. Based on these assessments, the interdependency of fossil-fuel resources on the one hand and the development of global energy demand on the other is analysed, and scenarios are derived for the future availability of oil and gas at a global level. The chapter continues with a brief description of the supply situation for coal.

In the light of the projected growth of demand for energy services, particularly electricity, there is a renewed interest in the extension of nuclear power in some countries. With uranium being a finite resource as well, Chapter 4 focuses primarily on the question of a future expansion of nuclear power in the context of the availability of nuclear fuels. Moreover, the evolution of the next generation of nuclear reactors, such as breeder reactors or reactors suitable for hydrogen production, is addressed.

Renewables are often seen as *the* future feedstock for hydrogen, if hydrogen is to make a real contribution to energy security and CO_2-emission reduction. However, 'cheap' renewable potentials are also limited and will be increasingly in competition with heat and electricity generation. An overview of the renewable potentials worldwide and with a particular focus on the situation in the European Union is at the centre of Chapter 5.

There is an urgent need for deploying carbon-dioxide capture and storage (CCS). This is a vital part of a portfolio of technologies and strategies, besides renewable energies and energy efficiency, that are required to reduce and eventually reverse CO_2-emission growth worldwide. With fossil fuels to remain a major primary energy source in the world for several decades to come – not least for the production of hydrogen during the initial phase – it is the only technology that could, potentially, directly achieve very large and rapid reductions in fossil-fuel emissions, although significant challenges still lie ahead. The various technical, economic and legal aspects of CCS are dealt with in Chapter 6.

Given the continuing growth of transport energy demand and showing the limits of fossil fuels in Chapter 3, Chapter 7 focuses on the potentials of alternative transportation fuels, including electricity. The chapter starts with a general overview of the different fuel supply options available. In the following, the major fuel pathways and their technical characteristics are described in more detail. The chapter concludes with a comparison of alternative fuels and drive systems based on a well-to-wheel analysis. This analysis accounts for the entire pathway (from feedstock to the drive system), the energy efficiency, CO_2 emission and costs and allows the important advantages and disadvantages of alternative fuels to be compared. On this basis, the major competitors for hydrogen are identified.

Chapter 8 first provides a brief overview of the evolution of hydrogen vehicles and points out major hydrogen demonstration projects around the globe. The development of a roadmap for hydrogen is essential because a widely accepted and harmonised hydrogen roadmap will give investors more planning security, will stimulate private and public R&D and is necessary for the establishment of an industry policy. To reflect the views of today's stakeholders about the introduction of hydrogen and fuel cells in the next decades, the status of roadmap development in the EU, the USA and Japan is thus another main issue in Chapter 8. In addition, the critical aspect of social acceptance of hydrogen, as a prerequisite for its introduction as vehicle fuel, is discussed.

Chapter 9 addresses the fundamental chemical and physical properties of hydrogen and how they play out when using hydrogen as vehicle fuel.

In Chapter 10, the most important (commercial) hydrogen production processes available today are described and analysed from the perspective of technology and economics, including their parameterisation for the hydrogen infrastructure model discussed in Chapter 14. Future development goals necessary to reach a market breakthrough of these processes, as well as novel hydrogen production technologies that still require basic research, are also addressed. The chapter finishes by discussing the use of hydrogen as industrial gas and the availability of industrial surplus hydrogen for fuelling hydrogen vehicles during the transition phase.

Chapter 11 addresses the critical question of hydrogen storage on board the vehicles. For hydrogen vehicles to reach competitive driving ranges, storage is crucial. There are still significant technical challenges to be overcome, which are discussed in this chapter.

Chapter 12 discusses and analyses the different options for hydrogen distribution – pipelines and trailers (including liquefaction) – from a technical and economic point of view, in the same way as the hydrogen production technologies in Chapter 10. Further, different hydrogen refuelling station concepts are described and the necessity for the development of codes and standards addressed.

Some of the most important benefits of hydrogen can only be realised if hydrogen is used in fuel cells; for example, the high overall conversion efficiency compared with the internal combustion engine as well as the reduction of local pollution and noise. Therefore, the market success of fuel cells plays a key role in a hydrogen economy. In Chapter 13, the fuel cell as a technology is introduced and its strategic role outlined. The chapter describes the various types of fuel cell and their potential uses in mobile, stationary and portable applications. As preparing for the structural changes in industry is just as important as the technical optimisation of fuel cells, the remainder of the chapter is devoted to this aspect.

Constructing a hydrogen infrastructure with user centres, a mix of hydrogen production technologies, plant sizes and locations, as well as related transport choices, is crucial and constitutes a challenging task for its introduction as vehicle fuel. In Chapter 14 different hydrogen infrastructure scenarios are developed and analysed. For the hydrogen infrastructure analysis, a model-based approach is described to assess its schedule and geography. What this build-up could look like, what it might cost and what the resulting CO_2-emission reductions in the transport sector are, are shown in a detailed case study for Germany, followed by more general strategies and conclusions at a European level. Closing the loop to the resource analyses in Chapters 3 to 5, this chapter concludes with some global hydrogen supply scenarios and their impacts on primary resource requirements.

While Chapter 14 focuses on a hydrogen infrastructure analysis for Europe, Chapter 15 addresses the build-up of a hydrogen infrastructure in the USA.

If hydrogen production is to be fully integrated into the energy system, a more holistic view needs to be applied with respect to its interactions with the electricity sector. The various aspects of the interplay between hydrogen production and electricity generation are addressed in Chapter 16. For instance, with growing capacities of wind power or photovoltaic generators, hydrogen could become a promising storage medium for surplus electricity from these intermittent renewable energies. On the other hand, with fossil fuels remaining the prevalent energy supply in the foreseeable future, despite their drawbacks with regard to climate change, routes to large-scale cost-effective hydrogen production with integrated CO_2 management for use in either power generation or as transport fuel are investigated. A special focus is on the technological and strategic aspects of co-production of hydrogen and electricity in integrated gasification combined-cycle (IGCC) power plants. Finally, from the perspective of overall CO_2-emissions reduction in the energy system, the question is addressed: whether renewable energies are better deployed in the transport sector or the power sector.

In the long run, hydrogen corridors offer, among other things, the chance to manage the energy resource limitations for hydrogen production within the EU and to improve energy supply security. Therefore, Chapter 17 deals with the assessment of possible hydrogen corridors between the EU and neighbouring countries, using consistent hydrogen scenarios, cost and potential calculations. Barriers for hydrogen corridors are also identified.

Often, only technical aspects are considered when looking at the deployment of hydrogen technologies. However, the introduction of hydrogen could have relevant implications for GDP, welfare and job development in a nation or region. The competitiveness of a nation could be one major driver for hydrogen use as an energy carrier. These issues are discussed in Chapter 18. Among others, possible economic effects are shown on the basis of a quantitative model analysis and assessed for relevant EU member states.

The results of Chapter 18 form the basis for the question of whether hydrogen technologies might be able to contribute to sustainable development by promoting both economic growth and environmental protection. The environmental issue is handled in Chapter 19, which integrates two debates: one on sustainable transport and the other on the future of hydrogen-powered transport technologies. Transport systems perform vital social functions, but in their present state cannot be considered 'sustainable'. Particular areas that need to be addressed in this respect include emissions, safety, land use, noise and social inclusion. Vehicle technologies will play a key role in addressing several of these areas. This chapter examines the role of hydrogen, and fuel-cell vehicle technologies in particular, in contributing to a future sustainable transport system and also shows the limitation of such an approach.

However, the question is whether our two major energy challenges of the future, climate change and shortcomings of conventional energy resources, can be solved by technical developments alone. The high losses at each level of energy conversion and use indicate that energy has to be used much more efficiently than is currently done. The importance of energy efficiency is at the centre of Chapter 20.

Chapter 21 summarises the major findings and conclusions of the book and reflects critically on the perspectives of a transition to a hydrogen-based energy and transport system.

Note on economic figures presented in the book

The majority of the economic figures, such as energy prices or capital costs of hydrogen technologies, presented in this book are expressed in euros (€), as they have been taken largely from European studies and literature sources. Past cost data or future projections have generally been converted into money of today. On the other hand, in various literature sources the cost data are indicated in US dollars instead of euros. The correct approach would be to apply the industrial-sector-specific inflation rate for each process to convert past cost data into today's costs and subsequently to convert the cost figures from US dollars to euros using today's exchange rates. This would have to be done for each process where the cost figures are indicated in US dollars.

The industry-specific inflation rate is different from sector to sector; also the inflation rate in the USA is different from that in the EU. In addition, the exchange rate between US dollars and euros has historically fluctuated to a large extent. It is assumed that the different inflation rates in the USA and the EU partly compensate for the error, which would be made if the exchange rate were assumed to be one euro per US dollar. To avoid modifying the figures indicated in the original literature sources, in this book the exchange rate is thus assumed to be one euro per US dollar.

The energy price scenarios and economic figures for hydrogen technologies and infrastructure build-up presented in the book date back mostly to the years 2005 and 2006. Across all industrial sectors, in the recent past, an unexpected and lasting surge in energy prices (above all, oil) has been experienced worldwide. For instance, the oil, gas and coal prices projected for 2030 in the high-energy price scenario in this book have already partially been exceeded by today's market prices of these commodities. However, the cost competitiveness of renewable energies as well as of hydrogen and fuel cell vehicles is positively influenced by this development, and hydrogen, on the basis of renewable energy sources, is the winner of such a development.

Steel and metal prices have escalated as well; this is manifested, for instance, in the drastic increase of capital costs for plant equipment or pipelines. For technologies with a high share of energy costs in total production costs, such as steam methane reformers, the impact of higher feedstock prices can significantly influence their economic attractiveness. This recent increase in energy and material or commodity prices has not been factored into the hydrogen supply costs. Hence, the absolute costs presented in this book have to be taken with caution, as they represent a rather optimistic estimate. Nevertheless, it has to be taken into account that the prices of conventional energy and vehicle technologies are also affected by the price increase.

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Why hydrogen?

Michael Ball

The world is facing a new era of energy anxiety with complicated choices regarding fuel sources, new technologies, and government regulations and actions. There is also a growing global consensus that greenhouse-gas emissions need to be managed, resulting in the challenge to search for the best way to rein in emissions while also providing energy to sustain economies. The projected increase in global energy demand, and the economic and geopolitical implications of possible shortcomings in the supply of oil have been major drivers stirring the debate about the future energy supply. Supply disruptions of oil would primarily hit the transport sector, since this is still almost entirely dependent on oil worldwide. This situation is increasingly triggering the search for alternative automotive fuels. In this respect, hydrogen has in recent years been gaining increased attention.

This chapter addresses why. First, the challenges of today's energy system – security of supply and reduction of greenhouse-gas emissions – will be discussed and existing and emerging energy policies to cope with them will be addressed. This sets the scene for the introduction of hydrogen, which needs to be seen in the context of the development of the global energy scene. The possible emergence of a hydrogen economy is then reflected from the perspective of historical transitions of energy sources. Next, the major drivers for the possible transition to a hydrogen economy will be outlined as well as the potential benefits that could be expected from using hydrogen as an energy vector.

2.1 The challenges of today's energy system

There are two major concerns about the future of the energy sector: *security of energy supply* and *climate change* (due to greenhouse-gas emissions, mainly CO_2).[1] Figure 2.1 demonstrates why. Global primary energy use per capita has increased

[1] Another issue is local air pollution, which is also linked to fossil-fuel combustion, not least in the transport sector. Especially in the world's growing megacities, road traffic has an increasingly negative impact on urban air quality (see also Chapter 19).

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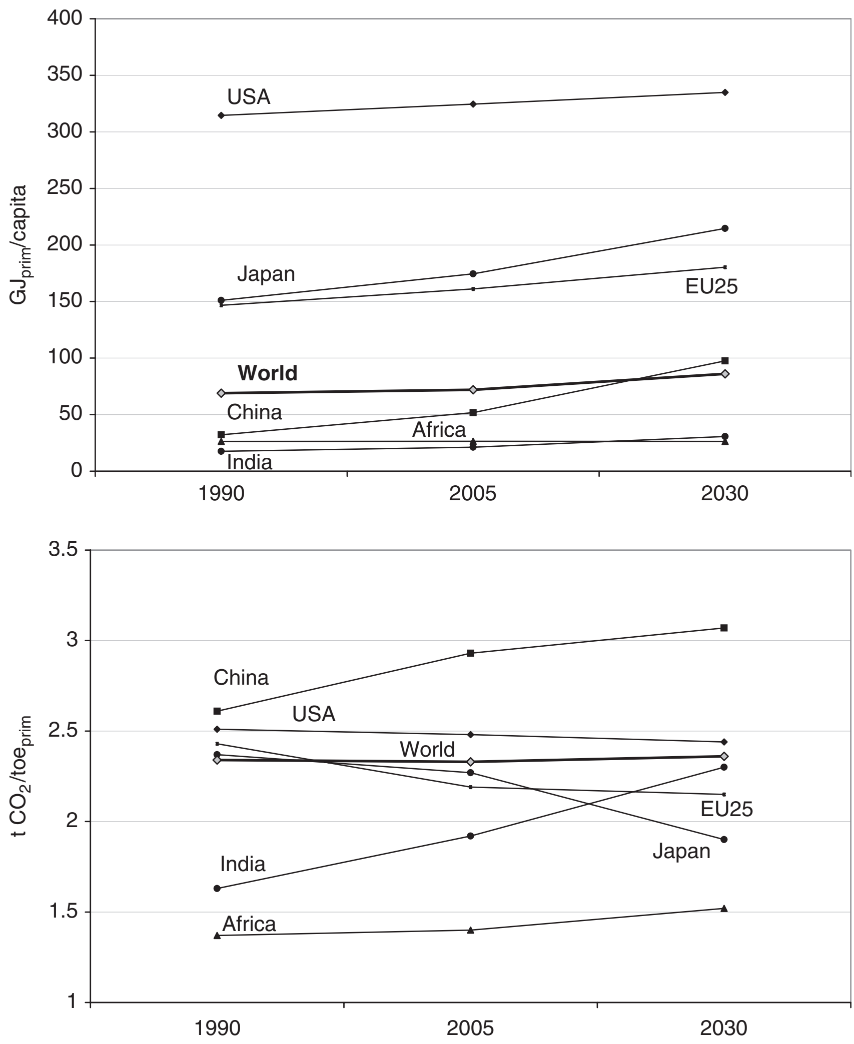

Figure 2.1. Development of global energy use per capita and carbon intensity (IEA, 2006; UNPD, 2006).

from 69 GJ/capita in 1990 to 72 GJ/capita in 2005 (a growth of 0.3% per year) and global carbon intensity has remained almost constant at 2.33 t CO_2/toe_{prim} (0.64 t C/toe_{prim}) (see also Fig. 2.10); both trends are projected to continue in the business-as-usual case until 2030 (IEA, 2006).

In 2005, the United States had, with 325 GJ/capita, the highest per-capita energy use, followed by Japan with 175 GJ/capita and the EU25 with 161 GJ/capita; the per-capita use of India and Africa amounted to 21 and 26 GJ/capita, respectively. It is not expected that energy use per capita will decrease. According to the

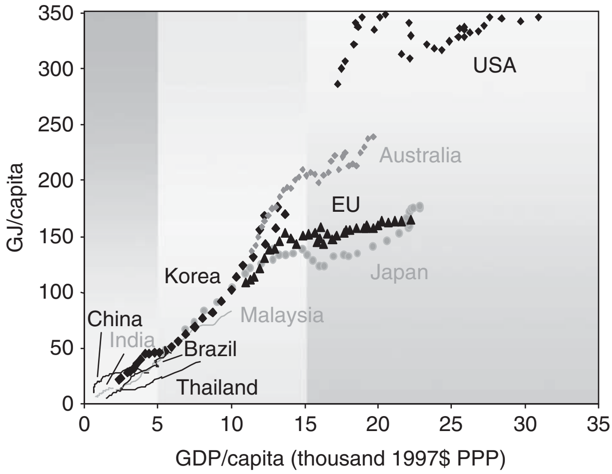

Figure 2.2. Climbing the energy ladder (Shell, 2001).

International Energy Agency (IEA), the average global energy use is projected to grow to 86 GJ/capita in 2030, according to their Reference Scenario (IEA, 2006).[2] The biggest growth rate, with more than 85%, is expected for China.

Energy is essential for economic development and rising living standards. Changes in the energy system mark transitions in the economic and social development of countries and societies, as they climb the energy ladder (Fig. 2.2). The first and most important step is substituting commercial for traditional fuels, such as biomass fuels and animal wastes, which are still the major energy source for people in many developing countries. After that there is a strong – but constantly changing – relationship between income and energy demand, with economic growth becoming increasingly decoupled from energy demand (Shell, 2001). When per capita GDP (on a purchasing power parity basis) reaches some:

- $3000 – demand explodes as industrialisation and personal mobility take off.
- $10 000 – demand slows as the main spurt of industrialisation is completed.
- $15 000 – demand grows more slowly than income as services dominate economic growth and basic household energy needs are met.
- $25 000 – economic growth requires little additional energy.

As basic energy needs are met, consumer priorities shift to other, often less energy-intensive, goods and services, pointing to eventual saturation of energy needs. However, in spite of a reduction in energy intensity (more energy saving, more efficiency in end uses), the rising demand for higher levels of comfort may still lead to a higher per capita consumption, as for instance projected for the US and EU25 in Fig. 2.1. Newly industrialising countries are able to climb the

[2] The IEA World Energy Outlook 2006 forms the basis for the analysis in this book (IEA, 2006). However, there are no fundamental changes in trends projected by the International Energy Agency (2008).