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Fossil Fuel Hydrogen

Technical, Economic and Environmental Potential

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To Maggie and Lola

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Those that have offered assistance or inspiration do not necessarily agree with the findings and opinions presented. Any errors or omissions are the responsibility of the authors alone.

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Acronyms

ACO	Automobile Club de l'Ouest
BCM	Billion cubic metres
BEV	Battery electric vehicle
BP	British Petroleum
CAGR	Compound annual growth rate
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CCUS	Carbon capture, Utilisation and Storage
CMR	Catalytic membrane reactor
CO	Carbon monoxide
CU	Carbon Utilisation
DAC	Direct air capture
DMFC	Direct methanol fuel cell
DOE	Department of Energy (USA)
ECBMR	Enhanced Coal Bed Methane Recovery
ENS	Enhanced natural sink
EOR	Enhanced Oil Recovery
EU-ETS	European Union—Emissions Trading Scheme
EV	Electric vehicle
FC	Fuel cell
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
H2	Hydrogen
HDS	Hydrodesulfurisation
HEV	Hybrid electric vehicle
HHV	Higher heating value
HP	High pressure
HTS	High-temperature superconductor
HYCO	Hydrogen–carbon monoxide
ICE	Internal combustion engine

IEA	International Energy Agency
IOC	International oil company
IT	Information technology
LH2	Liquid hydrogen
LHV	Lower heating value (equivalent to net calorific value)
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas (also “autogas” or “autopropane”)
MRI	Magnetic resonance imaging
NG	Natural gas
NOC	National oil company
O&M	Operations and Maintenance
ODS	Oxidative desulfurisation
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane
PHEV	Plug-in hybrid electric vehicle
POX	Partial oxidation
PPMW	Parts per million by weight
PSA	Pressure swing adsorption
SCW	Supercritical water
SCWU	Supercritical water upgrading
SER	Sorption enhanced reforming
SMR	Steam methane reforming
SOEC	Solid oxide electrolysis cell
SOFC	Solid oxide fuel cell
STP	Standard temperature and pressure
TGA	Thioglycolic acid
WGS	Water gas shift

Chapter 1
Introduction—The Hydrogen Economy Today

This book is focussed on the future. How can humanity ensure prosperity and mobility in the decades to come without irreversibly damaging our planet? One key imperative will be to reduce drastically the emission of harmful greenhouse gases, and most especially carbon dioxide. Today's mobility, based upon the combustion of petroleum, is a key component of concern going forward. Another climate challenge comes from the use of natural gas in domestic heating. Many voices argue that the future lies in electrification, the logic being that ways are known to generate electricity with very low harmful emissions, such as via renewable sources including wind and solar. Furthermore, the growing numbers of battery electric vehicles can allow one to imagine that the end of oil is in sight. Such a future may indeed occur, but we suggest that the end of fossil fuels is not inevitable and perhaps not even desirable if the risks to the climate can be avoided. The electrification path is not necessarily the only path associated with a low-carbon future and in this book we explore another—one that makes use of hydrogen as a future energy carrier and that seeks to minimise greenhouse gas emission via carbon capture, utilisation and storage. We use the term energy carrier, as opposed to "fuel" to make clear that hydrogen must be produced, using some other energy resource, as molecular hydrogen does not exist in sufficient accessible abundance on Earth.

Much attention has been given to the possibility of producing hydrogen from renewable energy sources, but in this book we deliberately give emphasis to an alternative: the continued production of hydrogen from fossil fuels, such as natural gas, but in ways that can be developed so as to minimise greenhouse gas emissions. Such a path of investigation will lead us to assess the merits of a widely held perception, especially prevalent among academic hydrogen economy researchers, that fossil-fuel-based hydrogen production methods are inevitably "*low tech, polluting and without significant potential for innovation*". In this book, we shed light on the realities of such methods in hydrogen production; we assess their future prospects and, where appropriate, we challenge false perceptions.

Figures from Ref. [1] reprinted under licence (number 4338730347221) from the International Journal of Hydrogen Energy.

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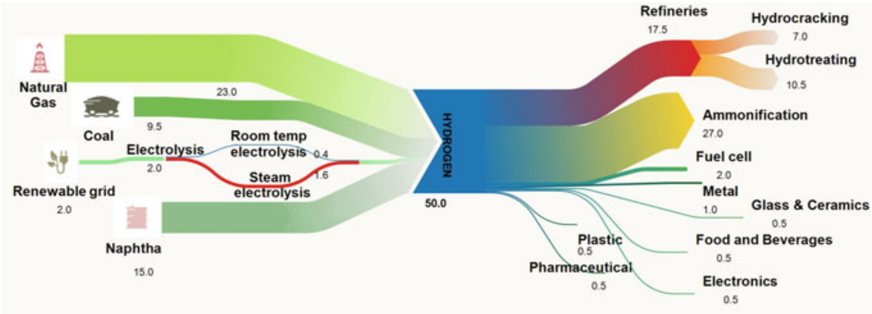

Fig. 1.1 Average supply and demand of global hydrogen supply, in million metric tons. Data assembled from multiple sources (2004–2013) [1]. The oil refining terms "hydrocracking" and "hydrotreating" are defined in the text

In this book, we take a whole systems approach and we consider current options and scenarios for the development of the hydrogen industry. We consider various strategic choices faced by both hydrogen producers and consumers. In so doing, we hope to reveal useful opportunities for the development of a robust well-functioning and growing hydrogen economy consistent with minimising harmful environmental impacts. Additionally, we seek to inform policy-makers on future trends for hydrogen commercialisation especially those emerging from today's industrial reality.

While the initial motivations for renewable energy came from early 1970s concerns surrounding oil supply security, more recently the driving motivation has been a desire to decrease the greenhouse gas emissions associated with transport and mobility. In this book, we shall describe renewables-based approaches to hydrogen production as the "Green Hydrogen" paradigm. Today "Green Hydrogen" represents a vision usually associated with renewable electricity generation, hydrogen production by electrolysis, new hydrogen supply chains, on-vehicle hydrogen storage and advanced fuel-cell-based electromechanical power trains for road vehicles.

Hydrogen is a well-established product of the industrial gas industry, and while its scale currently falls short of that associated with some scenarios for the much-vaunted "hydrogen economy", it is already a significant and important industrial activity. In this book, we shall sometimes refer to these well-established industrial activities as "Mature Hydrogen". In so doing, we avoid the terms "Brown Hydrogen" and "Blue Hydrogen" that are sometimes used so as to contrast with renewables-based "Green Hydrogen". We find the terms "Brown", for hydrogen from coal, and "Blue" for hydrogen from natural gas to be rather too simplistic, and perhaps even pejorative, for our purposes. The vast majority of today's hydrogen is sourced via Mature Hydrogen processes (see Fig. 1.1). Of this, a large fraction is associated with transport and mobility, as it is consumed by the petrochemical industry for removing sulphur from sour crude oil, and for producing less viscous petroleum-based vehicle fuels; this will be discussed further later in the chapter. The other major use for Mature Hydrogen is in fertiliser (ammonia) production.

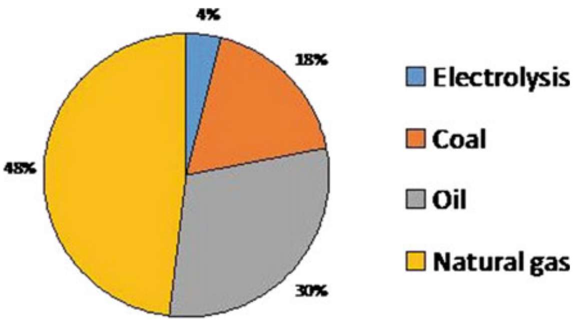

Fig. 1.2 Global hydrogen production [2, 3]. Note the electrolysis segment is 4% and the sequence in the key and diagram runs clockwise from there

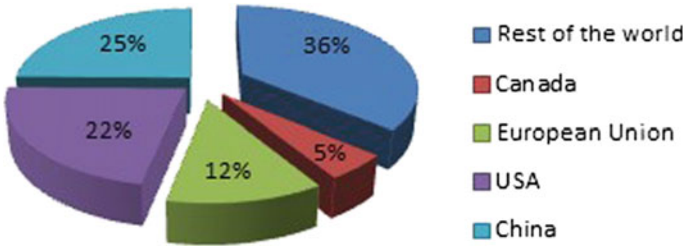

Fig. 1.3 Annual global hydrogen production (total is approximately 50 million metric tons). From: Bakenne and Nuttall, primary sources described therein [1]. Note the Rest of the World segment is the largest (36%), and the sequence in the key and diagram runs clockwise from there

Figure 1.1 reveals the scale of the Mature Hydrogen production industry today and further illustrates how this industry swamps the "Green Hydrogen" (renewable electricity to fuel cell) value chain. Such green flows represent only a tiny proportion of total hydrogen (by mass). In Fig. 1.1, the proportion from renewable electrolysis is shown as being 2%, and Fig. 1.2 shows the total coming from all electrolysis (using renewable and non-renewable electricity) to be 4%. Clearly, the proportion of hydrogen coming as Green Hydrogen from electrolysis using renewable electricity is currently very small.

As things stand today, Mature Hydrogen dominates hydrogen production, and hence, any process improvement within that industry, such as measures aiming to reduce greenhouse gas emissions, will have far more absolute beneficial impact than an equivalent proportionate improvement in the contribution from renewables-based Green Hydrogen, i.e. any 1% incremental improvement in the Mature Hydrogen sector would have an impact, in the short-term at least, equivalent to a 25% improvement to Green Hydrogen methods. These realities will persist for some time to come even in scenarios of significant growth in Green Hydrogen production. As such, Mature Hydrogen will clearly be dominant in all short-to-medium-term hydrogen futures (Fig. 1.3). This near-term reality in part motivates this book, but the question