TRANSITION TO HYDROGEN

Pathways Toward Clean Transportation

This book is a comprehensive and objective guide to understanding hydrogen as a transportation fuel. The effects that pursuing different vehicle technology development paths will have on the economy, the environment, public safety, and human health are presented with implications for policy makers, industrial stakeholders, and researchers alike. Using hydrogen as a fuel offers a possible solution to satisfying global mobility needs, including sustainability of supply and the potential reduction of greenhouse gas emissions. This book presents research on issues that are at the intersection of hydrogen and transportation, since studies of vehicles and energy carriers are inseparable. It concentrates on light-duty vehicles (cars and light trucks), set in the context of other competing technologies, the larger energy sector, and the overall economy. The book is invaluable for researchers and policy makers in transportation policy, energy economics, systems dynamics, vehicle powertrain modelling and simulation, environmental science, and environmental engineering.

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Foreword: on the transition to hydrogen

The transition to a sustainable energy supply is one of the major challenges that humans will face during the twenty-first century. This transition is inevitable, but there are many scenarios discussed for how and when this will happen. Humans have relied on renewable energy for most of history, and will do so again, as affordable supplies of fossil fuels decline in the coming decades (or centuries). However, there is wide agreement that the world should not give up the benefits of modern technology. The transition to a 'green' energy supply has already begun, and technologies for collecting and converting energy from the environment, new means of energy storage, and increased energy efficiency have progressed greatly. That is why there is legitimate hope that the coming change will be possible without a major reduction in the quality of life.

Individual mobility and long-distance travel have become vital elements of human existence. This mobility and the freedom it enables are taken for granted by most, and even considered a fundamental right. Most of this mobility is provided by the more than 900 million motor vehicles that now populate roads around the globe. An enormous number – and expected to grow to more than 1.1 billion in less than a decade. If all the motor vehicles on the globe were put bumper to bumper, the resulting giant traffic jam would be 4.5 million kilometres long, or wrap around the globe more than 100 times.

The vast majority of these vehicles are fuelled by gasoline and diesel – road transport is more than 96% reliant on fossil petroleum. It is obvious that sooner or later alternatives will be required. This will require a major transformation for our present society. From a historical perspective, the age of oil is a very brief and recent interlude that will disappear again soon. So the question is not if we are able to make this transition, but how we will manage it. Road transport is not the largest end-use for fossil energy, but technologically it is very challenging to change. Liquid hydrocarbons have a very high energy density and can be easily stored under ambient conditions onboard vehicles. Combustion engines are robust and reliable under different climates, and mass production has made them relatively affordable. Increasing the efficiency of conventional motor vehicles and their internal combustion engines is therefore the easiest and most efficient way to conserve energy and extend fossil energy reserves.

The energy sector will increasingly produce electricity from renewable resources; in Europe, this is mainly from wind power for economic reasons. The electrification of the automobile is therefore seen by many as an answer to the question of sustainable transport with energy stored onboard vehicles in the form of electrolytic hydrogen or in lithium batteries. Battery electric vehicles have a high tank-to-wheel efficiency. For well-defined driving patterns, and if recharging is possible while parked, a battery electric vehicle may offer the simplest substitute for a conventional car. Although a hydrogen system at first glance might appear less efficient and more complex, it also offers great potential to store large amounts of energy, which can be filled during off-peak hours where generation capacity exceeds demand. Thus, hydrogen may be available for vehicles as a valuable 'by-product' of the future energy sector. Hydrogen vehicles also profit from the high gravimetric energy density that hydrogen offers, i.e. hydrogen vehicles offer relatively large range and fast refuelling, with no limitation on vehicle size. The amount of on-board energy also allows for safety and comfort features that we are used to, such as heating and air conditioning, without sacrificing too much cruising range. A vehicle-use profile similar to that enjoyed with today's conventional cars will thus be possible with fuel cell cars.

Fuel cells, hydrogen technology, batteries, and electric propulsion systems – the technology elements that are needed for a transition to sustainable road transport– seem to be ready. A development path exists for these technologies, and cost figures and efficiencies are described in a sufficient detail. The question, however, remains how the shift from the current technology will take place. The new technologies are disruptive in the sense that they will change the automotive business in many ways. Electricity and hydrogen as energy carriers for transportation will require a completely different supply and distribution infrastructure compared to oil. Car manufacturers will also likely need to change their business model and their supply chain. Although it may require years or even decades until the change appears, it is likely that, once triggered, the transition will occur rather rapidly. Thus, it makes sense to prepare by developing technology and by playing through possible future scenarios.

Most of the scientific literature on the use of hydrogen and fuel cells for mobility focuses on the technology of vehicles and their components. To evaluate the ecological benefits of zero-emission vehicles propelled by electricity from hydrogen or batteries, it is also important to consider the path of hydrogen (or electricity) production, distribution, and supply. Only a true well-to-wheel calculation can provide the basis for comparing transport systems. Several studies have addressed well-to-wheel pathways, and this becomes a fairly complex task, especially if fluctuating sources like wind power must be taken into account. For example, analysing system efficiency becomes irrelevant if a battery cannot absorb all the charging energy available, or if charging energy is needed when renewable energy is scarce or unavailable.

The effects considered in a well-to-wheel analysis should include not only energy efficiency and CO_2 emissions, but also evaluate and compare second-order factors like particulate and SO_2 emissions and potential hydrogen losses. Furthermore, a fair comparison should incorporate life-cycle analysis of all relevant components, i.e. vehicles and infrastructure. Only the future will tell if the assumptions and calculations in this book are comprehensive and correct, or whether the scenarios proposed will materialise. However, the scenarios should indicate at least a basic direction in dependence between the assumed variables.

This book presents such a broad approach, providing a summary of well-to-wheel studies that incorporate a comprehensive set of parameters. As expected, there are no simple conclusions on the 'best' technology path, but the results of the studies presented may help us to understand the options and their implications for our ecology and economy. The results also show clearly that after the oil age has been left, it is unlikely a single well-to-wheel energy path will ever again account for 96% of the energy used for road transport.

Dr Rittmar von Helmholt

Preface

When the project that forms the basis for this book was initiated in 2006, hydrogen was enjoying immense popularity as a possible alternative to fossil fuels as an energy storage vector. Record-breaking attendance at fuel cell exhibitions was common, and the news media was full of the ambitious market introduction plans of fuel cell company representatives and the grand hopes of politicians. It is now 2011, and the euphoria surrounding hydrogen has shifted to batteries and all-electric vehicles; the 'electron economy' is being advertised in much the same way. Hype surrounding transportation technology is a common phenomenon, and history provides us with many examples of announcements of 'major breakthroughs'. Some, like fuel injection, caught on; others, like the 'Nucleon' nuclear powertrain, did not. Whether hype hampers or helps society to find and to implement the best solutions for our pressing social and environmental problems is debatable. What is certain is that a thorough analysis of technological alternatives, and perseverance in execution once the best solution (or set of solutions) has been identified, should never be superseded by action plans driven by media attention.

The Alliance for Global Sustainability is the framework that facilitated collaboration between John Heywood's group at the Massachusetts Institute of Technology and Alexander Wokaun's team at the Paul Scherrer Institute in investigating vehicle technology alternatives 'Before the Transition to Hydrogen'. With generous financial support from the Swiss Competence Center for Energy and Mobility (CCEM), these two working groups met biannually with sponsors and partners from industry and professional associations, to share ideas and to engage in exciting multidisciplinary research. The results of the Swiss team's research are contained in this book. Even though, occasionally, the opinions of the partners from opposite sides of the Atlantic regarding the potential of the various transportation energy technologies investigated did not converge, the collaboration was highly successful because of the high value that both research teams placed on objective and unbiased analysis. In particular, the MIT group's strength in combustion engine technology and policy research proved to be highly complementary to the PSI group's technical know-how regarding fuel cells, global energy system modelling, and scenario analysis.

This book was facilitated to a large degree by the professionalism of the very capable chapter authors who contributed content, peer-reviewed each other's work, and participated in lively discussions enabling effective quality control. The challenge inherent in pulling together five PhD dissertations that focused on very different aspects of hydrogen in transportation was never overwhelming, and the editors gratefully acknowledge the support of all 15 authors. We would like to specifically thank Dr Philipp Dietrich for contributing his technical support throughout the project and for providing his invaluable assistance with this book as part of the group of authors. We are deeply indebted to Dr John Heywood for his unwavering engagement in the 'Before the Transition to Hydrogen' project together with the members of his analysis team.

That this book so quickly found a publisher, and that our sponsors continue to be interested in our results and supportive of our efforts, testifies to the fact that, although hype can support magazine sales, only objective analysis can support good ideas.

Executive summary

Increasing the security of the supply of energy for transportation and reducing environmental impacts from personal vehicles are prominent among the great challenges of the twenty-first century. To investigate pathways toward achieving these goals, a wide variety of analytic approaches are used in this book including life cycle assessment, heuristic vehicle design and drivetrain simulation, evaluation of hydrogen emissions from industry and transportation, modelling of technology innovation and market penetration, as well as energetic and economic modelling of future transportation scenarios. This coordinated effort has analysed a broad portfolio of technology options and implementation strategies with an emphasis on hydrogen as a transportation fuel. A summary of the main conclusions follows.

Reducing energy use – Reducing overall energy use depends on the combination of vehicles, drivetrains, energy carriers, and energy resources. Hybrid technologies can reduce non-renewable vehicle energy use by 10–60% (from mild hybrid to plug-in series hybrid architecture). Reducing vehicle weight using the lightweighting technologies considered can reduce energy use by 0.2–5% (keeping vehicle size and powertrain constant). Switching from current fuels to alternate fuels or electricity can reduce vehicle energy use by 5–75%, depending on the fuel or electricity mix considered. Electric vehicles shift conversion efficiency losses from the car to the power plant, so the maximum primary energy saving is not 75%, but rather about 40–60%, depending upon the efficiency of generation.

Reducing CO_2 – Hydrogen only represents an attractive transportation fuel for meeting stringent CO_2 reduction targets if it is produced using primary energy resources with zero or low CO_2 contents. Life cycle assessment of fuel production and consumption pathways reveals that there are several alternatives to conventional fuels that offer slight reductions in CO_2 emissions, but only a few that reduce

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CO_2 by more than 50%. The highest reduction is achieved by using electricity from renewable or nuclear sources in electric vehicles. The next most effective is using hydrogen produced by electrolysis, followed by hydrogen produced from fossil fuels with carbon capture and storage.

Hydrogen production – Starting with the surplus capacity of current industrial hydrogen production reduces the barriers to the development of hydrogen production and distribution. A range of concepts is available for both centralised and decentralised hydrogen production from low-CO_2 primary energy. The associated costs are significant, but comparable with the anticipated costs of adaptation to a changing global climate.

Hydrogen emissions and levels – A future energy system using hydrogen for 10% of the total final energy demand by the end of the twenty-first century will likely have anthropogenic emissions of molecular hydrogen to the atmosphere that remain in the same range as today's levels of hydrogen emissions. The clear advantages of hydrogen-based transportation in reducing greenhouse gases and other pollutant emissions are therefore unlikely to be accompanied by any relevant negative effects due to the hydrogen leakage.

Increasing security – The insecurity of supply represented by an oil-based transportation system is based on both the geographic unevenness of the resource distribution and the rising cost of the remaining supplies. As the transportation sector shifts to a different mix of primary energy resources and energy carriers, we can expect that the primary energy resources (gas, coal, nuclear, and renewables, in particular, biomass and solar energy) will have both increasingly long time horizons and generally broader geographic distributions. The shift in energy carriers (from conventional fuels to synfuels, hydrogen, and electricity) will be increasingly regional. Both of these changes tend to increase the security of supply.

Restructuring the transportation sector – Achieving stringent climate protection goals in order to restrict a rise in global temperature will require a thorough restructuring of the global energy system at a significant cost. Radical changes in the transportation system will be integral to this restructuring, with dynamic shifts in the market shares of competing vehicle technologies. Self-reinforcing interactions between citizens, car manufacturers, and industry, as well as regulators and governments will be required. In addition to financial incentives, the inherent attractiveness of the environmentally friendly technologies will be of key importance in driving these changes.

Regional differences – Regional studies and fleet simulations show that the emerging solutions will differ between continents and regions. Regional availability of fossil fuels will favour the continued use of conventional and hybrid technologies, while the market entry of alternative technologies will depend on the availability of biofuels, on the one hand, and on cost reductions for battery electric and fuel cell vehicles, on the other.

Policy measures – Policy measures are needed to support the transition to a clean transportation system in both the short and long term. Global scenarios clearly show that, in the absence of climate policy, only low-cost measures, such as lightweighting and the introduction of hybrid technologies, are likely to be implemented. Only strict greenhouse gas targets would encourage biofuels and transportation based on renewable and/or nuclear energy. Hydrogen fuel cell vehicles represent an attractive option for a climate policy that limits atmospheric CO_2 concentrations to 450 ppm.

In summary, no single solution exists to facilitate the transition to a clean and secure future transportation system. Advanced conventional and hybrid vehicles running on conventional, synthetic, or biomass-derived fuels are expected to co-exist for decades with electric vehicles based on rechargeable batteries and fuel cells. Low CO_2 electricity is expected to make an important contribution to lowering the greenhouse gas footprint of transportation, both by direct use in battery electric vehicles for shorter driving ranges and for decentralised hydrogen production.

While change can only come gradually, the changes required to deal with the global transportation energy problem will require a paradigm shift in perceptions and attitudes that must be led by individual countries, communities, and stakeholder groups. The developed world's technology and economic resource advantages mean that it will necessarily lead the supply side of implementing such shifts in the transportation sector, while the developing world's greater growth rates mean that it can play a proportional role in redesigning transportation demand.

Abbreviations

ATR	autothermal reformer
BAU	business-as-usual
C	carbon
CADC	Common Artemis Driving Cycle
CC	combined cycle
CCS	carbon capture and storage
CED	Cumulative Energy Demand
CGR	coal gasification and reforming
CH	Switzerland
CH_4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
DDP	deterministic dynamic programming
EC	European Commission
ECU	engine control unit
EEFSU	Eastern Europe and Former Soviet Union
E_{H2}	hydrogen emission factor
E_{CO}	carbon monoxide emission factor
Empa	Swiss Federal Laboratories for Materials Science and Technology
EPR	European pressurised reactor
FAO	Food and Agriculture Organization of the United Nations
FCV	fuel cell vehicle
GDP	gross domestic product
GHG	greenhouse gas
GMM	global multi-regional MARKAL (model)
ΔH	enthalpy change
H_2	hydrogen

H_2/CO	molar ratio of hydrogen to carbon monoxide
H_2O	water
HDA	heuristic design algorithm
HEV	hybrid-electric vehicle
HFCV	hydrogen fuel cell vehicle
HHV	higher heating value
HVDC	high-voltage direct current
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
J	joule(s)
Kph	Kilometres per hour
l	litre(s)
LAFM	Latin America, Africa, and the Middle East
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
LDV	light-duty vehicle
LHV	lower heating value
LPGV	liquefied petroleum gas vehicle
m	metre(s)
MAGICC	Model for the Assessment of Greenhouse-Gas-Induced Climate Change
MARKAL	market allocation (model)
MCDA	multi-criteria decision analysis
MOX	mixed oxide
NAM	North America
NEDC	New European Driving Cycle
NGV	natural gas vehicle
NMVOC	non-methane volatile organic compounds
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O_2	oxygen
OECD	Organisation for Economic Cooperation and Development
OEMS	original equipment manufacturers
OOECD	Other Organisation for Economic Cooperation and Development
OH	hydroxyl radical

PE	primary energy
PM	particulate matter
ppmv	parts per million volume
PSA	pressure swing adsorption
PSI	Paul Scherrer Institute
PV	photovoltaics
PWR	pressurised water reactor
RD&D	research, development, and demonstration
RES	reference energy system
rpm	revolutions per minute
SCR	solar carbo-thermic reduction of Zn/ZnO
SMR	steam methane reforming
SNG	synthetic natural gas
SRES	Special Report on Emissions Scenarios (of the IPCC)
STD	solar thermal dissociation of Zn/ZnO
t	metric tonne(s)
TWC	three-way catalytic converter
UCTE	Union for the Co-ordination of Transmission of Electricity
VKT	vehicle kilometres travelled
VSM	vehicle substitution model
W	watt
WEUR	Western Europe
WGR	wood gasification and reforming
Wh	watt-hour
WHO	World Health Organization
λ	lambda

Abbreviations for tonne (t), watt (W), watt-hour (Wh), and metre (m) are combined with the following prefixes to indicate larger amounts:

E	exa–	10^{18}
G	giga–	10^{9}
k	kilo–	10^{3}
mg	milligrams	10^{-3}
mg/km	milligrams per kilometre	10^{-3}
ppb	parts per billion	10^{-9}
ppm	parts per million	10^{-6}
Tg	teragrams	10^{12}
Tg/year	teragrams per year	10^{12}