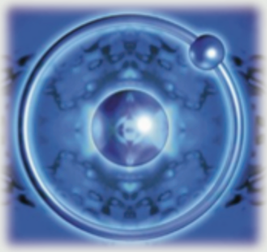
GREEN CHEMISTRY AND CHEMICAL ENGINEERING

HYDROGEN ENERGY *and* VEHICLE SYSTEMS



Edited by

Scott E. Grasman

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HYDROGEN ENERGY *and* VEHICLE SYSTEMS

GREEN CHEMISTRY AND CHEMICAL ENGINEERING

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Series Preface

The subjects and disciplines of chemistry and chemical engineering have encountered a new landmark in the way of thinking about, developing, and designing chemical products and processes. This revolutionary philosophy, termed *green chemistry and chemical engineering*, focuses on the designs of products and processes that are conducive to reducing or eliminating the use and/or generation of hazardous substances. In dealing with hazardous or potentially hazardous substances, there may be some overlap with and interrelationship between environmental chemistry and green chemistry. While environmental chemistry is the chemistry of the natural environment and pollutant chemicals in nature, green chemistry proactively aims to reduce and prevent pollution at its very source. In essence, the philosophies of green chemistry and chemical engineering tend to focus more on industrial application and practice rather than academic principles and phenomenological science. However, as both a chemistry and chemical engineering philosophy, green chemistry and chemical engineering derives from and builds upon organic chemistry, inorganic chemistry, polymer chemistry, fuel chemistry, biochemistry, analytical chemistry, physical chemistry, environmental chemistry, thermodynamics, chemical reaction engineering, transport phenomena, chemical process design, separation technology, automatic process control, and more. In short, green chemistry and chemical engineering is the rigorous use of chemistry and chemical engineering for pollution prevention and environmental protection.

The Pollution Prevention Act of 1990 in the United States established a national policy to prevent or reduce pollution at its source whenever feasible. In adhering to the spirit of this policy, the Environmental Protection Agency (EPA) launched its Green Chemistry Program in order to promote innovative chemical technologies which reduce or eliminate the use or generation of hazardous substances in the design, manufacture, and use of chemical products. The global efforts in green chemistry and chemical engineering have recently gained substantial support from the international communities of science, engineering, academia, industry, and governments in all phases and aspects.

Some of the successful examples and key technological developments include the use of supercritical carbon dioxide as green solvent in separation technologies; application of supercritical water oxidation for destruction of harmful substances; process integration with carbon dioxide sequestration steps; solvent-free synthesis of chemicals and polymeric materials; exploitation of biologically degradable materials; use of aqueous hydrogen peroxide for efficient oxidation; development of hydrogen proton exchange membrane (PEM) fuel cells for a variety of power generation needs; advanced biofuel productions; devulcanization of spent tire rubber; avoidance of the use of chemicals and processes causing generation of volatile organic compounds (VOCs); replacement of traditional petrochemical processes by microorganism-based bioengineering processes; replacement of chlorofluoroacrbons (CFCs) with nonhazardous alternatives; advances in design of energy efficient processes; use of clean, alternative, and renewable energy sources in manufacturing; and much more. This list, even though it is only a partial compilation, is undoubtedly growing exponentially.

This book series on green chemistry and chemical engineering by CRC Press/Taylor & Francis Group is designed to meet the new challenges of the 21st century in the chemistry and chemical engineering disciplines by publishing books and monographs based upon cutting-edge research and development to the effect of reducing adverse impacts upon the environment by chemical enterprise. In achieving this, the series will detail the development of alternative sustainable technologies that will minimize the hazard and maximize the efficiency of any chemical choice. The series aims at delivering the readers in academia and industry with an authoritative information source in the field of green chemistry and chemical engineering. The publisher and series editor are fully aware of the rapidly evolving nature of the subject and its long-lasting impact upon the quality of human life in both the present and future. As such, the team is committed to making this series the most comprehensive and accurate literary source in the field of green chemistry and chemical engineering.

Sunggyu Lee

Foreword

The gasoline crisis way back in the 1970s produced an initial awareness on the part of the general public about the finiteness of popular energy sources. Since that time, enthusiasm by the public, investors, and government administrations has surged and waned for various technologies viewed as possible “silver bullet” answers to the energy needs of developed and developing nations. In more recent years, a more realistic notion has been adopted by many that there probably are no technology silver bullets but rather that an “all of the above” technological approach is needed.

Hydrogen technology can be one part of a comprehensive energy approach. While hydrogen enthusiasts tout the inherent cleanness of this basic element found prolifically in nature, detractors like to point out the challenges and costs of producing, storing, and using hydrogen on a large scale. While the debate between enthusiasts and detractors influences the level of interest by governments and the public, thankfully there are engineers and scientists in academia and industry that continue researching, developing, and applying hydrogen technologies toward ever more practical solutions.

This book provides insights from many of those scientists and engineers on a broad array of issues, challenges, and accomplishments of hydrogen technology over the past years leading to the present. As for the future for hydrogen technology, whether the glass is half full or half empty may be a matter of perspective. However, hydrogen technology seems certain to have a role in our energy future.

William R. Taylor

Preface

Purpose and Audience

Hydrogen shows great promise both as an energy carrier and as a fuel for transportation, portable, and stationary sources; however, the expanded use of hydrogen as a renewable energy source raises a number of concerns and challenges that complicate planning efforts. Organizations are researching, developing, and validating hydrogen pathways to establish a business case for market implementation. However, significant research and educational challenges still must be addressed.

The use of hydrogen technologies addresses critical societal issues related to energy security, stability, and sustainability. First, hydrogen may be produced from local resources, thus eliminating the need for complex energy/fuel supply lines. Second, hydrogen, used in conjunction with renewable energy sources, provides a stable method of energy/fuel production. Third, hydrogen produced from renewable sources provides clean, emission-free energy/fuel.

Hydrogen technology constitutes a highly interdisciplinary field that extends from the fundamentals of materials, electrochemical processes, and fuel processing/storage systems, to complex design concepts for hybrid vehicles, and renewable power/fuel systems. Infrastructure analysis, market transformation, public policy, safety, and environment also play key roles. Additionally, sustainable energy systems is an emerging field that aims to develop new and improved energy technologies, systems, and services, while understanding the impact of energy on the economy and society.

Hydrogen technology research encompasses traditional engineering disciplines (biological, chemical, electrical, environmental, geological, material science, mechanical, systems), sciences (biology, chemistry, mathematics, physics), social sciences (economics, psychology), and business. Thus, the book addresses transformational interdisciplinary research in the emerging field of sustainable energy systems to disprove common misconceptions regarding hydrogen technologies and demonstrate that hydrogen technologies are a viable part of a sustainable, stable, and secure energy infrastructure.

The book addresses a new comprehensive approach to the applications of hydrogen-based technologies aimed at integrating the transportation and electric power generation sectors to improve the efficiency and reliability of both systems. Improving the overall efficiency and performance of any/all stages will decrease costs and improve market penetration, which is critical to the long-term success of hydrogen technologies. The book also addresses intelligent energy management schemes for hydrogen energy and vehicle systems, as well as safety and environmental science related to hydrogen technologies and the infrastructure required to provide for safe, renewable-hydrogen options.

Major themes of this book are focused on hydrogen fuel and fuel cell technologies (including safety and environmental science), hydrogen vehicle systems, hydrogen energy systems, and hydrogen infrastructure and marketing strategies. Whereas other books focus on specific aspects of hydrogen (e.g., materials, fuel processing, fuel cell electrochemistry), this book aims to be a comprehensive look at state-of-the-art research in hydrogen energy and vehicle systems.

There is strong interest in hydrogen as an energy carrier that has gained support from industrial companies and a continuously growing level of government backing. While the establishment of a sustainable hydrogen economy is seen as key to long-term environmental and economic stability, achieving these societal benefits involves a variety of stakeholders on regional, national, and global levels. Thus, this book will do the following:

- Provide the basis for pursuing a broad research agenda to develop, demonstrate, evaluate, and promote the long-term successful use of hydrogen-based technologies
- Develop resources to attain, coordinate, and articulate stable and independent energy benefits

This book is appropriate for researchers and professionals in energy-related fields, faculty in related disciplines, students in related majors, and policy makers. It may be used as a reference for the practitioner or for university courses, short courses, and workshops. For example, courses are being taught as part of integrated energy curriculum in over 250 related programs. These courses have titles such as Energy Systems, Alternative Energy/Fuels, Hydrogen Systems, Fuel Cell Applications, Automotive Fuel Cell Systems, and Renewable Systems.

Authored by experts in the field, the book will clearly and accurately present a comprehensive resource on hydrogen systems. It provides a balanced presentation of hydrogen technology from both theoretical/technical and application perspectives. Based on current research in hydrogen energy and vehicle systems, it connects hydrogen technology through proper systems analysis and integration, including both quantitative and qualitative factors, and includes all stakeholder perspectives, including energy and environmental perspectives of hydrogen technologies.

Overview of the Book

The chapters published in this book are authored by over 25 researchers affiliated with higher education institutions and/or research centers. The chapters cover a range of theory and application and are grouped into three sections.

Section I: Hydrogen Energy and Fuel Cell Modeling

Chapter 1: Hydrogen and Electricity: Parallels, Interactions, and Convergence

This chapter discusses some of the major ways that a future hydrogen economy would interact with the electricity sector and how the transportation and stationary fuels sectors and the electricity sectors might converge. H2 and electricity are both zero-carbon, flexible, useful, and complementary energy carriers that could provide power for a wide range of applications. Hydrogen is touted as an important future transportation fuel in the light-duty sector because of its storage characteristics, efficiency, and emissions. In addition, an important consideration for the evolution of the energy system is the competition and synergies for the use of energy resources for producing H2 and electricity.

Chapter 2: Hydrogen Infrastructure: Production, Storage, and Transportation

This chapter provides a review of hydrogen production, storage, and transportation technologies. The production technologies selected represent promising near- and long-term options based upon state of technology, scale of production quantities, and environmental impacts. The production technologies include steam methane reformation, gasification, electrolysis, and thermochemical conversion. Compressed gas, liquid, cryo-compressed, metal hydride, and surface adsorption storage methods are presented based on the scale of hydrogen storage capability. The chapter concludes with a discussion on transportation methods and operational characteristics for an expanded hydrogen infrastructure.

Chapter 3: PEM Fuel Cell Basics and Computational Modeling

This chapter discusses the operational principles of polymer electrolyte membrance (PEM) fuel cells and presents models incorporated into a commercial software package. The models are evaluated against independent data reported in the literature for its suitability to predict the performance of PEM fuel cells. The findings establish a model capable of simulating PEM fuel cells with a reasonable degree of accuracy and the low computational intensity inherent to analytical modeling. Given the software environment the model is implemented in, this could be of significant aid to the design and optimization of fuel cell- and hybrid-powered vehicles.

Chapter 4: Dynamic Modeling and Control of PEM Fuel Cell Systems

This chapter discusses the basic principles of fuel cells including the history and different types of fuel cells along with their properties, structure, and applications, with a special focus on polymer electrolyte membrane (PEM) fuel cells. Auxiliary devices needed for safe and efficient operation of PEM fuel cells are also introduced. Some well-known control-oriented dynamic models of PEM fuel cell components are presented. Simulation analysis of a typical PEM fuel cell is conducted based on the dynamic control-oriented models. Finally, commonly used control algorithms, such as oxygen excess ratio and temperature regulation, are presented and implemented using the control-oriented models.

Section II: Market Transformation and Applications

Chapter 5: Market Transformation Lessons for Hydrogen from the Early History of the Manufactured Gas Industry

This chapter explores the future for hydrogen by delving into the history of the manufactured gas industry, drawing comparisons and contrasts, and highlighting potentially valuable analogies and lessons. It examines various side-by-side comparisons between the two energy systems, including physical and chemical properties, costs, production processes, and system configurations, and examines infrastructure developments over time, reviewing five major phases in the history of manufactured gas. It concludes with five key analogies or lessons for hydrogen based upon this historical review.

Chapter 6: Fuel Cell Technology Demonstration and Data Analysis

This chapter strives to provide an independent third-party technology assessment that focuses on fuel cell system and hydrogen infrastructure performance, operation, maintenance, and safety. U.S. government-funded hydrogen and fuel cell demonstrations support technology research and development, and researchers at the National Renewable Energy Laboratory (NREL) are working to validate hydrogen and fuel cell systems in real-world settings. A key component of these demonstrations and deployments involves data collection, analysis, and reporting. NREL's Hydrogen Secure Data Center (HSDC) was established in 2004 as the central location for data analysis and works with DOE and its fuel cell award teams to collect and analyze data from these early deployment and demonstration projects. The analysis is regularly updated and published by application and is summarized in this chapter.

Chapter 7: Producing Hydrogen for Vehicles via Fuel Cell–Based Combined Heat, Hydrogen, and Power: Factors Affecting Energy Use, Greenhouse Gas Emissions, and Cost

This chapter introduces the concept of producing fuel for hydrogen-powered vehicles using combined heat, hydrogen, and power (CHHP) systems based on stationary high-temperature fuel cells, which also provide electricity and heat to buildings. In addition, it explores the factors affecting the performance of CHHP systems in various locations as well as the associated greenhouse gas (GHG) emissions and hydrogen cost. The energy, GHG, and hydrogen cost implications of this technological strategy for facilitating efforts to establish a fueling infrastructure to support early hydrogen vehicle markets have been modeled; the analysis employs the FCPower model, which was developed by the National Renewable Energy Laboratory and is available for download as an Excel spreadsheet. This chapter explains some of the basic modeling assumptions underlying the representation of MCFC systems in the FCPower model and reviews the total energy use, emissions, and hydrogen cost for CHHP installations in comparison to conventional supplies of energy to buildings and small-scale dedicated (SMR) production of hydrogen.

Chapter 8: Hybrid and Plug-in Hybrid Electric Vehicles

The introduction of high-power and high-energy dense lithium-ion-based electrochemical storage technologies has provided the necessary transformative advance to bring forth the recent focus on hybrid and plug-in hybrid electric vehicles. Hybridization of hydrogen combustion and hydrogen fuel cell propulsion systems can provide benefits similar to those seen with conventional vehicles. This chapter will discuss the benefits and consequences of the various hybrid electric vehicle propulsion architectures as they are applied to hydrogen propulsion technology. These architectures have varying benefits to the propulsion system based on their ability to influence the output power of the vehicle relative to the goal of the vehicle hybridization. Further, the difference between hybrid and plug-in hybrid electric vehicles represents a varying degree of energy storage that must be considered with the size, class, and intent of the vehicle propulsion system. The appropriate application of the hybrid vehicle architecture with an accompanying energy management control will be crucial to the advancement of these vehicles.

Chapter 9: Hydrogen as Energy Storage to Increase Wind Energy Penetration into Power Grid

This chapter presents an analysis of a full wind and hydrogen integration. This study is a part of the activities carried out in the framework of the IEA Hydrogen Agreement, Task 24 "Wind Energy and Hydrogen Integration." As a result of the study, it is concluded that hydrogen could compete with other energy storage systems, mainly in energy applications linked to renewable energies such as wind power. Hydrogen can be stored for a future reconversion into electricity or can be used in a different application, taking advantage of its energy vector feature. Although there are still several disadvantages and technical problems to be solved, it presents optimism concerning the future of hydrogen in the energy sector. The chapter also discusses applications for hydrogen such as CHP and CHHP.

Chapter 10: Hydrogen Design Case Studies

This chapter discusses real-world applications of hydrogen technologies for a hydrogen community. The applications are generic and are applicable for communities around the world. They include a commercial hydrogen fueling station, residential hydrogen fueling, hydrogen applications for airports, and other hydrogen applications. These conceptual designs were created by the Missouri University of Science and Technology's hydrogen student design team in response to the Fuel Cell Hydrogen Energy Association (formerly known as National Hydrogen Association) Hydrogen Student Design Contests.

Section III: Hydrogen Safety

Chapter 11: Hydrogen Safety

This chapter discusses hydrogen safety in a "hydrogen infrastructure" setting such as hydrogen fueling stations, hydrogen vehicle research and development garages, hydrogen storage, and stationary fuel cell installations—each with different risks and potential hazards. Hydrogen has many properties that make it unique including wide flammability limits, low ignition energy, high diffusivity, and low flame visibility. With proper understanding of these properties, incorporating experience, and safe handling procedures, hydrogen can be used in a safe working environment.

Chapter 12: Hydrogen Fuel Cell Vehicle Regulations, Codes, and Standards

This chapter covers regulations, codes, and standards (RCS) for hydrogen fuel cell vehicles. The chapter covers both domestic vehicle standards found primarily in Society of Automotive Engineers (SAE) and CSA Standards (CSA) documents and international standards found primarily in International Organization for Standardization (ISO) standards. The chapter does not cover the motor vehicle safety regulations promulgated by federal transportation safety agencies outside of the United States. The basic purpose of these RCS is to ensure safe operation of fuel cell–powered vehicles. These RCS do not cover the infrastructure required to support these vehicles. The infrastructure requirements are well developed in the United States, but they are outside of the scope of this chapter.

Acknowledgments

In addition to the authors of the chapters, the completion of this book has involved the efforts of several people.

The editor is grateful to anonymous reviewers for their insightful comments and suggestions for improvements to individual chapters. The chapter submissions were subject to a blind refereeing process that engaged up to three reviewers per chapter. Without these efforts, this book could not have been completed. The editor is particularly grateful to series editor Sunggy "KB" Lee, Fermin Mallor, and William Taylor for assistance in the development of the book.

Last, but not least, the editor would like to acknowledge the help of the CRC/Taylor & Francis team, particularly Amber Donley and Allison Shatkin, as their assistance and patience have been significant.

Scott E. Grasman
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About the Editor

Scott E. Grasman is a professor and department head of Industrial and Systems Engineering at Rochester Institute of Technology. He has had previous appointments in Engineering Management and Systems Engineering at Missouri University of Science and Technology, Operations and Manufacturing Management in the Olin Business School at Washington University in St. Louis, Statistics and Operations Research at the Public University of Navarre, and Universitat Oberta de Catalunya. He received BSE, MSE, and PhD degrees in industrial and operations engineering from the University of Michigan. He has relevant industrial experience, including collaborations on research and curriculum activities.

His primary research interests relate to the application of quantitative models, focusing on the design and development of supply chain and logistics networks. Dr. Grasman has been a principal or co-principal investigator on projects with support from, among others, Air Force Research Lab, Argonne National Labs, Army Engineer Research and Development Center, Bi-State Development Agency, Boeing, Defense Logistics Agency, Ford, General Motors, Government of Spain, Intel Research Council, Missouri DoT, Missouri Research Board, NSF, SAP America, Semiconductor Research Corporation, TranSystems, U.S. Department of Education, U.S. Department of Energy, U.S. Department of State, U.S. Department of Transportation, Walmart Logistics, and others. His work has resulted in being the author or coauthor of over 100 technical papers, including multiple best conference paper awards, as well as reviewer/editorial roles for various technical journals and books.

Dr. Grasman has significant expertise in the areas of operations research, management science, and supply chain and logistics systems. Within these areas, he has developed mathematical models that aid managerial decision making by generating theoretical and applied solutions to important problems. He has provided solutions for random yield production systems, manufacturing processes (e.g., headcount allocation, cross-training, and scheduling), enterprise integration, (e.g., integrated inventory/transportation systems and collaborative SMEs), and information sharing through connective technologies. Recent and on-going studies have focused on alternative fuels programs, public–private partnerships in transportation, alternative energy infrastructure modeling/simulation, and sustainability in supply chain and facility logistics. His research also addresses energy/engineering education. Dr. Grasman is a member of ASEE, IIE, and INFORMS. His email is Scott.Grasman@rit.edu.

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Jennifer Kurtz is a senior engineer at the National Renewable Energy Laboratory on the Hydrogen Technology Validation team. As part of this team, Kurtz processes, analyzes, and reports on real-world data of fuel cell projects that span many fuel cell markets such as vehicles, forklifts, stationary, and backup power. Prior to joining NREL in 2007, she worked for six years at UTC Power, primarily in fuel cell system design and components. Kurtz received her master's degree in mechanical engineering from Georgia Tech and her bachelor's degree in physics from Wartburg College.

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Andrew Meintz received his BS in electrical engineering from Missouri S&T in 2007. He continued his education at Missouri S&T toward a PhD as a U.S. Department of Education GAANN Fellow. His research interest is in power electronics, electrochemical energy storage systems, and hybrid electric vehicles. In 2008 and 2009 he interned at Sandia National Lab, first studying the effects of plug-in hybrid vehicles on the power grid and then on the stability effects of high photovoltaic penetration of an island grid. Beginning in 2009, he was involved with the Department of Energy–sponsored EcoCAR: The NeXt Challenge, a three-year colligate competition to design and build fuel-efficient vehicles. As part of this challenge he designed, built, and tested a fuel cell plug-in hybrid vehicle. This led to his work on the vehicle, the energy management control design, and a vehicle simulator. Since completing his degree in December of 2011, Meintz has started his career with a position at General Motors as a high-voltage battery systems engineer.

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Todd Ramsden specializes in the technical and economic analysis of fuel cell systems and supporting hydrogen infrastructure at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. He currently focuses on the performance and market potential of fuel cell systems for automotive and material handling applications and life cycle assessments of energy use and greenhouse gas impacts of various potential hydrogen production and distribution pathways. Ramsden has extensive experience in the transportation sector, analyzing energy, greenhouse gas, and air pollution issues. He currently works in the Hydrogen Technologies and Systems Center at NREL. Prior to his work at NREL, he held positions at the U.S. Department of Transportation, Ford Motor Company, and the U.S. Environmental Protection Agency.

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Hydrogen and Electricity: Parallels, Interactions, and Convergence

Christopher Yang

CONTENTS

1.1 Introduction

The current energy system is comprised of a number of distinct energy carriers whose infrastructures have evolved over the course of the 20th century. The main fuels and energy carriers that consumers and end users use include petroleum fuels (gasoline and diesel), natural gas, and electricity. The transportation sector has been primarily powered by liquid petroleum fuels, while buildings and other end uses have relied on natural gas and electricity.

Recently, concerns about air pollution, oil and energy insecurity, and greenhouse gas emissions have been driving a search for cleaner energy sources and alternative energy carriers for all sectors, especially in the transportation sector. In particular, the last few decades have seen a renewed interest and significant research and development on electric drive vehicles, including battery electric vehicles, hybrid electric vehicles, and hydrogen fuel cell vehicles. Though there has been a great deal of activity in research and development, only a tiny fraction of our transportation energy use does not rely on petroleum.

While hydrogen has been touted primarily as a transportation fuel, it can serve a number of other potential needs and the potential development of a future hydrogen economy could significantly change the energy system because of linkages between hydrogen and the existing electricity system. The unique characteristics of electricity and its long history have resulted in an extensive infrastructure that converts primary energy resources such as fossil fuels, nuclear energy, and renewable energy resources into electricity and distributes the electricity to consumers essentially everywhere in the developed world. Any hydrogen infrastructure development can potentially take advantage of this expansive network of energy resource extraction and transport and electricity generation and distribution systems. The new energy system can also utilize the advantages of hydrogen to complement the use of electricity in some applications. And the development of a hydrogen energy system can take different forms depending upon how integrated a future one imagines for the co-evolution of the hydrogen and electricity systems.

1.1.1 Standard View of H_2 and Fuel Cells

Much of the interest and research in H_2 and fuel cells has been in the transportation sector, with many automotive companies developing low-temperature proton exchange membrane (PEM) fuel cell vehicle research, development, and demonstration (RD&D) programs in the last decade [1, 2]. Oil companies that primarily supply transportation fuels have also been involved with RD&D projects for H_2 production and refueling. Significant research and development is also being carried out on stationary fuel cells for use in the electric sector. However, hydrogen infrastructure is widely viewed as a transportation fuel supply system to be used in connection with fuel cell vehicles. Most stationary fuel cells do not require a ubiquitous hydrogen infrastructure since they are able to run on hydrocarbon fuels such as natural gas, which already has an extensive distribution infrastructure. Vehicles, on the other hand, require a widespread infrastructure to produce, store, transport, and dispense pure hydrogen at a network of refueling stations [3–6].

Because of the focus on hydrogen use in the light-duty transportation sector, the standard view of many in and out of the field is that hydrogen is a transportation fuel that will compete with and could potentially displace gasoline and diesel. Many hydrogen-related analyses and research programs focus primarily on hydrogen as a vehicle fuel [7–11]. Hydrogen and fuel cells are touted as an excellent alternative to gasoline and combustion vehicles because of their benefits with respect to efficiency, resource requirements, and environmental attributes [1, 8, 10–13]. The hydrogen infrastructure needed to extract, transport, and convert a primary energy feedstock to H_2 and store, transport, distribute, and dispense that hydrogen for use in personal vehicles is also analogous to the exploration, refining, distribution, and dispensing infrastructure for gasoline and diesel fuels. This focus can be thought of as an evolutionary model of H_2 and fuel cells because they are viewed as merely cleaner and more efficient technologies that will be used for light-duty vehicles. This framework is convenient because it does not fundamentally change the way that people view transportation fuels that power their vehicles. Hydrogen is merely a replacement for gasoline and fuel cells are a replacement for internal combustion engines.

1.1.2 Integrated View of H_2 and Electricity

In an alternative view, H_2 fuel and fuel cells are not merely replacements for specific components in the conventional transportation paradigm. Instead, they represent a new path that will be integrated with the electricity system, forming a future energy system with two primary energy carriers (hydrogen and electricity). There are multiple reasons for this convergence of hydrogen and electricity into an integrated hydrogen and electric energy system, including their complementary attributes as energy carriers, their potential production from the same primary energy resources, and their ability to be coproduced and interconverted.

H_2 and electricity are two decarbonized energy carriers that have very different yet complementary characteristics, which suggest specific uses and applications for each. With the emerging scientific, political, and public consensus on climate change, there will be an increasing impetus for reducing and eventually decarbonizing our energy system. Hydrogen and electricity are two energy carriers that enable conversion, transport, and utilization of a wide variety of primary energy resources in a decarbonized energy system.

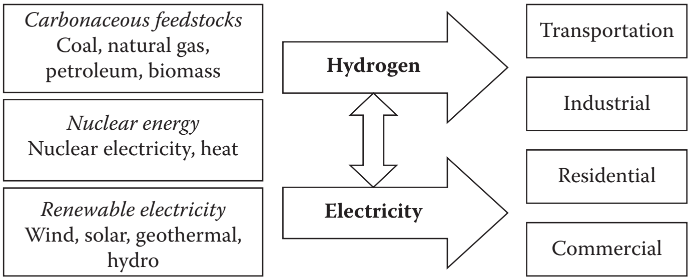

FIGURE 1.1
Schematic showing the parallel nature of hydrogen and electricity from the perspective of the energy resources and end-use sectors. (From Yang, C., *International Journal of Hydrogen Energy,* 33(8), 1977–1994, 2008.)

Another basic idea supporting the concept of hydrogen and electricity convergence is that hydrogen and electricity can and will be produced from the same primary energy resources and feedstocks, such as natural gas, coal, and biomass (see Figure 1.1). There are benefits associated with having another energy carrier, especially one that can be used in transportation applications that can be made from a large number of primary energy resources. However, this would also lead to a direct competition for the fossil, nuclear, and renewable energy resources that are used to produce each energy carrier.

The third argument for the convergence of hydrogen and electricity is related to the potential for their coproduction and interconversion. A number of studies have investigated production plants that can be used to generate both hydrogen and electricity [14–22]. In many of these studies, there are a number of benefits associated with producing both energy carriers in the same plant, including improved efficiency and lower costs. Interconversion is one of the most tangible examples of the shift toward a more integrated energy economy based upon hydrogen and electricity. With current energy carriers, there is little opportunity to convert between various forms. In addition, the widespread use and supporting infrastructure for these dual energy carriers may provide reliability benefits for consumers.

Figure 1.2 presents two different views of the hydrogen reactions in a fuel cell and electrolyzer. The "electrochemical" view shows the fuel cell reaction (on the right) that produces electricity when hydrogen and oxygen combine to form water and the electrolysis reaction (on the left) where electricity is required as an input to split water into hydrogen and oxygen. In this view, electricity and hydrogen have different roles: hydrogen is merely an enabler, while electricity is the primary focus (i.e., either the product or the input). This view is common when focusing on the end use of hydrogen—for example, if one thinks of a fuel cell vehicle as an electric vehicle that obtains its electricity from hydrogen.

The interconversion view describes the exact same reactions but emphasizes the conversions between energy carriers rather than the conversion between reactants and products of the electrochemical view. This alternative view

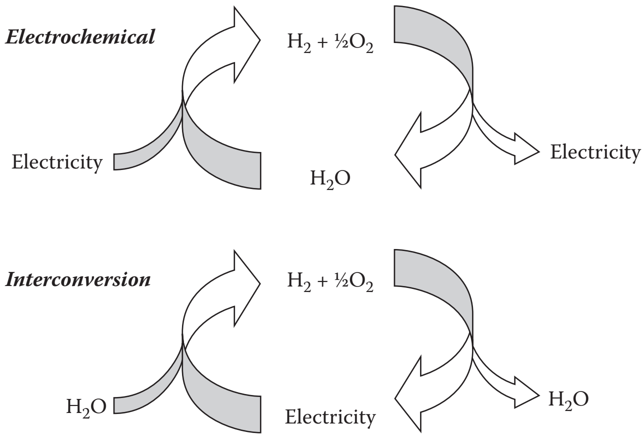

FIGURE 1.2
Alternative views of hydrogen and electricity reactions. The electrochemical view shows electricity as either an input or an output of chemical reactions, and the interconversion view shows water as an input or output of the conversion between H_2 and electricity. (From Yang, C., *International Journal of Hydrogen Energy*, 33(8), 1977–1994, 2008.)

shows that H_2 (plus O_2) and electricity are merely different forms of the same energy carrier that result from the addition and removal of water. Hydrogen is the hydrated form and electricity is the dehydrated form. This view emphasizes the large impacts that hydrogen production and conversion would have throughout the energy system, on the production, transmission, and conversion of energy. It is not the case that one view is better or worse than the other, but the significance of these two views is that they help to make clear, by emphasizing these different aspects, the relationship between H_2 and electricity.

This chapter will discuss many of the important elements that arise from the convergence between hydrogen and electricity as energy carriers, including possible opportunities and challenges. The goal is to help readers identify key areas of these future interactions and how they may impact the potential evolution of the future energy system.

1.2 Hydrogen and Electricity Parallels

Both hydrogen and electricity are energy carriers rather than energy sources, because they do not occur naturally but rather must be produced from other energy resources such as fossil fuels or renewables. A key similarity between hydrogen and electricity is that they are both zero-carbon and pollution-free energy carriers at the point of use and can have a wide range of *life cycle* emissions in bringing these energy carriers to the point-of-use.

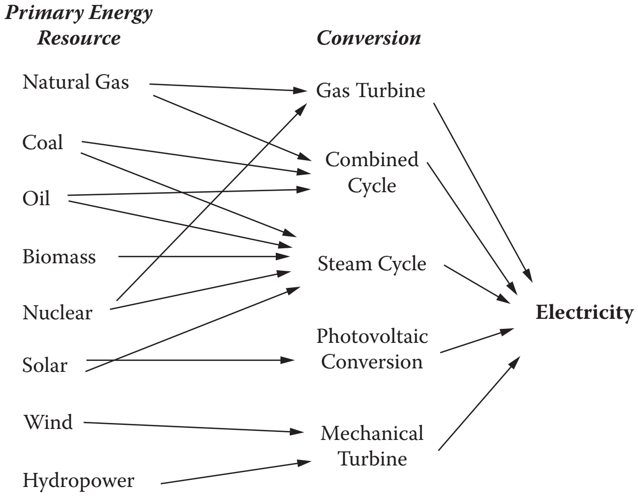

FIGURE 1.3
Resources and conversion technologies for electricity generation. (From Yang, C., *International Journal of Hydrogen Energy*, 33(8), 1977–1994, 2008.)

1.2.1 Generation Resources

As with electricity, hydrogen can be produced from a range of production methods and feedstocks. Figure 1.3 and Figure 1.4 show the potential resources for producing each energy carrier and their similarities. This is a major change, as hydrogen enables the possibility of using these resources

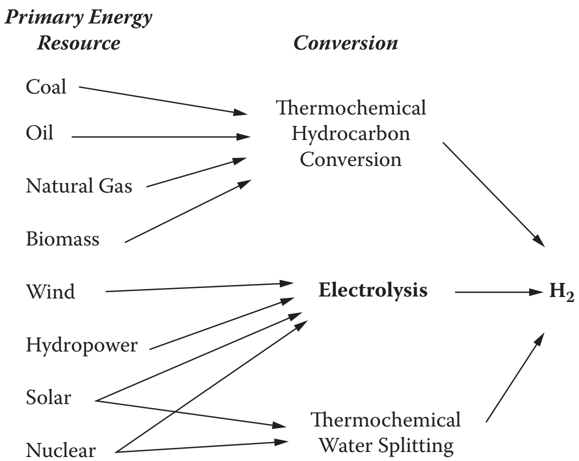

FIGURE 1.4
Resources and conversion technologies for hydrogen production. (From Yang, C., *International Journal of Hydrogen Energy*, 33(8), 1977–1994, 2008.)

in the transportation sector, which is currently, and has traditionally been, reliant on and restricted to petroleum.

Decarbonized, clean energy carriers that have multiple production pathways are valuable because they allow policies and resource constraints to affect the upstream side of the supply system without any inconvenience, or even knowledge of these changes, to consumers. Currently, a number of states have enacted a renewable portfolio standard (RPS), which mandates a specified fraction of electricity generation that must come from renewable resources, such as wind, solar, geothermal, and biomass. And while RPS targets are expected to increase over time, this process is transparent to the end user. Similarly, the ability to produce hydrogen from a wide range of resources enables producers, over time, to alter the mix of hydrogen production, so that it can be made less polluting and with lower greenhouse gas emissions as costs for these technologies declines. In fact, California has enacted a law (SB1505) that links state funding for hydrogen refueling stations to the renewable content and greenhouse gas emissions profile of the hydrogen that it dispenses (requiring a 30% reduction in greenhouse gas emissions and a goal of 33% renewable).

1.2.2 Generation Mix

Because of the variations in electricity demand that occur over the course of a day, and seasonally, and the difficulty in storing electricity, the electric power system consists of a number of power plants of different sizes and types, which are fueled by a number of energy sources. This structure has evolved because not all power plants need to be operating at full capacity all the time. Excess electricity generation that is not used cannot be stored efficiently and is thus wasted, so generation is carefully managed to make sure that there is the correct amount of generation occurring. Different types of power plants have different capital and operating costs associated with them, so some will be operated continuously while others will be operated only when demand is highest.

Hydrogen demand will also vary over the course of a year and the required output from a hydrogen production plant will not be constant over an entire year. While hydrogen can be stored more easily than electricity, it is not as inexpensive to store as a liquid fuel and hydrogen will likely not be stored for more than a few days. This means that variations in demand that occur on a longer timescale (i.e., seasonally) must be handled by the production plants themselves. Depending upon the extent of demand variation, it may be economically advantageous, like with the electric power system, for supply to consist of a mix of plants, with differing capital and operating costs, to minimize the cost of meeting demand.

1.2.3 Distribution and Infrastructure

Electricity is a commodity that is produced at hundreds or thousands of generating power plants in a given region and placed upon a common transmission and distribution infrastructure and then distributed nearly universally. Hydrogen infrastructure could also consist of a common network of hydrogen delivery that links a number of production facilities to the end users. Using H_2 primarily as transportation fuel would require delivery to a network of refueling stations spread throughout a region. If hydrogen were distributed to homes and businesses, an extensive network of pipelines would be needed that is similar to the network of natural gas distribution pipelines.

An analysis of regional hydrogen fuel infrastructure for supplying hydrogen FCVs in the U.S. states of Ohio and California indicates that because of economies of scale, having fewer large production plants provides lower cost fuel than many more smaller plants even if transportation distances are greater [6]. And while there are few production plants, they feed a common hydrogen delivery system that distributes hydrogen regionally to refueling stations in different cities.

1.3 Complementarity and Convergence

1.3.1 Complementary Attributes and Applications

H_2 and electricity are two decarbonized energy carriers that have very different yet complementary characteristics, which suggest specific uses and applications for each. Given the importance of reducing GHG emissions to avoid dangerous anthropogenic climate change, the use of decarbonized energy carriers is essential over the next few decades. Electricity is already in widespread use, and there is already a system for producing and distributing electricity from multiple sources to end users. Thus, switching to lower GHG-emitting sources of electricity can be done in a manner that is hidden from the end user with no disruption on their part.

The direct use of fuels for transportation and combustion applications (boilers, burners, and other applications) is currently optimized around the specific characteristics of the fuels they use (typically natural gas, gasoline, and diesel) and cannot generally be switched to lower- or zero-carbon fuels without upgrading to new technologies. There is the potential to use liquid biofuels to replace conventional fuels, but even in these situations, ethanol and biodiesel cannot replace gasoline and diesel without some modifications to current vehicles and engines. There also appears to be significant limitations in the amount of biofuels that can be sustainably produced [23, 24]. As a result, there are many benefits to the use of hydrogen in many of these applications that rely on direct use of fuels. These will be discussed in the context of the specific applications—vehicles and stationary applications.