Preface

Hydrogen is the most abundant element in the universe. It was first identified in the 1850s, during the industrial revolution, when a new type of society had emerged with the invention of the steam engine and its rapid transformation of the world's standard of living. In this mechanization era, the energy from coal was converted to mechanical power by steam engines, while the world shifted from a feudal system to widespread industrialization and capitalism. A second industrial revolution followed in the twentieth century—called the electrification era—when mechanical power from steam produced by large-scale power plants was used to supply national and regional grids with electricity. Industrial water electrolysis and fossil fuel reforming technologies to generate hydrogen for many types of industrial processes became well established since the early 1900s. A new self-conscience of society developed towards a concern for sustainable development whereby anthropogenic activities would neither harm the environment nor jeopardize the access of future generations to valuable materials and energy resources for their needs. In this context, the development of a hydrogenation era emerged in this current century, with respect to sustainable hydrogen generation at a large scale and its use as a clean energy carrier or chemical feedstock for industrial processes.

Hydrogen is the basic constituent of many chemical compounds with high industrial and societal value. Combined with nitrogen from air, hydrogen can be converted to ammonia—a fertilizer, refrigerant, and key compound for a large variety of pharmaceuticals and chemicals. Combined with carbon dioxide, ammonia gives urea, another valuable fertilizer which is generally produced today in a polluting and non-sustainable manner. Hydrogen combined with carbon dioxide can yield methanol. Also, other synthetic fuels such as diesel or gasoline can be produced by hydrogenation of carbon dioxide, making it possible to develop a cleaner transportation sector for road vehicles. It is envisaged that fuel cell vehicles will be become widely available in the coming decades. This will require a major increase in hydrogen demand, for example, by hundreds of millions of tonnes annually. Upgrading of heavy oil and oil sands in Alberta, Canada, is another need for hydrogen in vast quantities. Sustainable hydrogen production is also needed for cleaner steel production, plastics, construction materials, etc.

The key challenge of the emerging hydrogen era is to generate hydrogen at a large scale in a sustainable manner. This is a key question which has preoccupied scientists and engineers for decades. One needs a feedstock resource containing hydrogen such as water, hydrogen sulfide, or fossil hydrocarbons. Furthermore, one needs a source of energy which is "clean(er)" to extract hydrogen from the selected resource. In addition, the method should generate hydrogen as efficiently as possible. Nuclear-based hydrogen production is an important pathway to sustainable hydrogen production at a large scale. In principle, nuclear energy to generate hydrogen can lead to: (1) better efficiency, (2) better cost-effectiveness, (3) better resource use, (4) better knowledge through design and analysis, (5) better energy security, and (6) better environment. These are six main pillars for sustainable energy development of humankind.

The use of nuclear energy to generate hydrogen as an energy carrier was first proposed for military applications in the 1960s when a small, mobile nuclear reactor was proposed to generate hydrogen from water by electrolysis which could then supply fuel for heat engines. The main benefit of nuclear energy is the compactness of the energy source. A nuclear plant can generate 1 MW per acre of footprint at a high capacity factor, whereas other sustainable sources are much less dense (for example, concentrated solar power generates 25 kW per acre with a capacity factor smaller than 0.3). Nuclear fuels are extensively available worldwide, especially with the new breeding reactor technology, which makes use of thorium.

The first chapter of this book presents a general perspective on hydrogen as an energy carrier including its historical evolution and related concepts and technologies, as well as hydrogen's applications for sustainable energy in two major sectors: residential and transportation.

The second chapter discusses the role of nuclear energy for sustainable hydrogen generation at a large scale. The capacity factor of a nuclear power plant can be increased to high values (over 95 %) if hydrogen is produced locally, either by electrolysis or other processes linked to the nuclear reactor. The use of hydrogen for heavy oil and bitumen upgrading, as well as its positive environmental impact, is also discussed. In addition, hydrogen use in road vehicles, rail, and air transport is analyzed for various case studies.

Chapter 3 summarizes the main nuclear hydrogen production programs worldwide over the last ~40 years. The Generation IV International Forum (GIF) is as an international organization that coordinates the development of the next generation of nuclear reactors for electricity, hydrogen, and process heat production. There are six main reactor concepts in GIF and a roadmap established for a synergistic and cooperative development among the international partners. These partners include the U.S. Department of Energy, Euratom (European Union), Japan Atomic Energy Agency, International Nuclear Energy Association, Commissariat of Atomic Energy (France), Korean Atomic Energy Research Institute, Natural Resources Canada, China Atomic Energy Authority, and Paul Scherrer Institute (Switzerland), among others. Other non-GIF concepts that have been developed in countries such as Russia, India, South Africa, and Brazil are also presented. A case study of a recent international consortium for copper–chlorine cycle development is highlighted.

Chapter 4 presents water electrolysis technology including the fundamental science and technology. Alkaline, proton exchange membrane and solid oxide electrolyzers are discussed in detail. In addition, other emerging hybrid electrolysis systems are discussed. The main systems of nuclear-electrolytic hydrogen production from water are outlined.

Thermochemical water splitting cycles are comprehensively examined in Chap. 5. Fundamentals of thermochemical and electrochemical reactions are introduced. The general methodology of thermochemical and hybrid cycle construction and assessment is described. The selected chemical reactions must be thermodynamically feasible, but also having satisfactory equilibrium yield. A down-selection procedure of thermochemical and hybrid cycles is presented. The main development aspects of three of the most promising cycles are discussed in detail. These include the sulfur–iodine cycle, the hybrid sulfur cycle, and the copper–chlorine cycle.

Chapter 6 focuses on the promising copper–chlorine cycle, which has experienced rapid development and progress in recent years.

Chapter 7 involves integrated systems for nuclear hydrogen production. This chapter explains all six nuclear reactor concepts selected in the GIF roadmap. Further sections are focused on a linkage of the very high temperature reactor (VHTR) with steam electrolyzers, integration of VHTR with the sulfur–iodine cycle, integration of a nuclear plant with the hybrid sulfur cycle, and integration of a copper–chlorine thermochemical cycle with a supercritical water cooled reactor (SCWR). A case study is presented for integrated nuclear, desalination, and hydrogen production technologies.

The concluding Chap. 8 presents future trends and emerging opportunities with nuclear hydrogen production. A series of newly developed concepts of systems and high-temperature components and materials is presented. Also, various advanced power cycles coupled to fission reactors and thermochemical water splitting plants are discussed. In addition, nuclear fusion technology for hydrogen generation is briefly examined. This is a long-term prospective technology, which is expected to be developed mostly beyond the 2050s.

This book provides extensive analyses and compilations, as well as the fundamentals of the main processes, technological problems, and design challenges. Nuclear hydrogen generation is an emerging technology which links the physics of nuclear reactors with the chemistry of hydrogen production processes, as well as the engineering of integrated systems that perform many simultaneous functions which are complex because they generate multiple outputs (e.g., electricity and hydrogen).

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