HYDROGEN ENERGY

PRINCIPLES AND APPLICATIONS

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WILEY

Hydrogen Energy

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Principles and Applications

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"The energies of our system will decay, the glory of the sun will be dimmed, and the earth, tideless and inert, will no longer tolerate the race which has for a moment disturbed its solitude. Man will go down into the pit, and all his thoughts will perish."

ARTHUR BALFOUR, The Foundations of Belief (1895)

"The future is green energy, sustainability, and renewable energy."

ARNOLD SCHWARZENEGGER (2018)

"Energy, like the Biblical grain of mustard seed, will move mountains (because) a man doesn't need brilliance or genius, all he needs is energy."

HOSEA BALLOU and ALBERT GREENFIELD (2022)

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Preface

Since the late 1960s, there has been an increased awareness of a wide range of energy issues covering all sources: fossil fuels, nuclear, solar, geothermal, etc. More and more people are becoming aware of energy concerns. It is now increasingly important that all individuals develop capabilities in this area, including those who do not possess an understanding of many energy problems or have the proper information available when involved with energy issues. In addition, all professionals should have a basic understanding of the technical and scientific terms related to energy issues. One of the key issues that has emerged in this century is how hydrogen can effectively evolve as a green energy alternative. Hopefully, this text will serve the needs of those interested in increasing their knowledge of this form of energy and its relation to the energy problems facing society.

The current human population on Earth is approximately seven billion, and it will increase in the future. The influence and effects of human activities on energy use have become increasingly evident at the local, state, national, and international levels. Particular interest in hydrogen energy has recently surfaced and the net result is that there has been a more significant increase in both awareness and analysis of hydrogen energy options since the turn of this decade.

Hydrogen may well emerge as a very important fuel by the middle of this century. Since hydrogen is not a basic energy resource except in the sun, it must be obtained by using some other basic energy resource to generate hydrogen from water or other hydrogen-containing chemical compounds. It is an ecologically friendly fuel that is presently used in the propulsion of spacecraft and can potentially be mass-produced and commercialized for electric generation, energy storage and all forms of transportation.

It should be noted that free hydrogen is found only in very small traces in the atmosphere, but solar and stellar spectra show that it is abundant in the sun and other stars. In combination with other elements, it is widely distributed on Earth, where the most important and abundant compound of hydrogen is water, H_2O. It is a component of all the constituents of living matter as well as of many minerals. It forms an essential part of all hydrocarbons and a vast variety of other organic substances. All acids contain hydrogen; the distinguishing characteristic of an acid is its dissociation, upon going into solution, to yield hydrogen ions.

In addition, hydrogen is known to exist in three isotopic forms. The nucleus of each atom of ordinary hydrogen is composed of one proton. Deuterium, present in ordinary hydrogen to the extent of 0.02%, contains one proton and one neutron in the nucleus of each atom and has an atomic mass of 2. Tritium, an unstable, radioactive isotope, contains one proton and two neutrons in the nucleus of each atom and has an atomic mass of 3.

Given the above, hydrogen (H_2) fuel is certain to play a major role in the U.S.'s transition towards a "carbon-neutral" economy. No doubt more of the secondary energy sources for the

future will be hydrogen produced from both renewable and nonrenewable sources. It is anticipated that in the near future, hydrogen energy will support numerous jobs with revenues well over $100 billion and could become a major player in satisfying up to 15–20% of the US energy demands.

The authors considered and then decided to write a text on hydrogen energy that highlighted pragmatic rather than theoretical issues. It contains three parts and provides material that can also be used in teaching a course sequence intended to serve as a training tool for those individuals involved with and those interested in entering the hydrogen energy field. Although the literature is inundated with texts emphasizing theory and theoretical derivations, the goal of this book is to present this subject of hydrogen energy from a strictly applied perspective.

The book is the result of over 4 years of effort by the authors. The first rough draft was prepared during the years 2020 through 2022. The manuscript underwent significant revisions during the past year, some of it based on the experiences gained from earlier written material. It should also be noted that the authors cannot claim sole authorship of all of the written material in this text. Although the bulk of the material is original or taken from sources that the authors have been directly involved with, every effort has been made to acknowledge material drawn from other sources.

As noted in the Table of Contents, this hydrogen energy book is divided into three parts:

Part I: Energy Overview
Part II: Select Hydrogen Energy Topics
Part III: Technical Engineering Issues

Part I provides an introduction and broad overview of energy-related topics. Following Chapter 1 that contains a glossary of terms, the reader is introduced to energy issues, energy resources, and environmental policy and regulations. Part I concludes with chapters concerned with thermodynamics and fuel cells. Part II – the heart of the book – provides select hydrogen energy topics. Chapter headings include a hydrogen energy overview, government programs, hydrogen physical/chemical properties, hydrogen-bearing compounds, processing, storage, transportation/transmission, conversion, uses, and the hydrogen byproduct water. Part II concludes with a chapter on safety consideration for hydrogen technologies. Part III is concerned with engineering applications. It features chapters on such topics as environmental health and hazard risk assessment, energy–environmental interactions, ethical considerations, and economics. This is followed by a chapter concerned with system optimization. The final chapter of the book provides nearly 50 illustrative examples beginning with elementary thermodynamic calculations and culminating with three optimization applications employing linear programming in their solution. To summarize, the proposed text provides information on the:

Properties
Fundamentals
Engineering Principles
Regulations
Thermodynamics
Sources
Processes
Ethical Considerations
Economics
Optimization Calculations Associated with Hydrogen Fuel

Thus, this book can serve as either a guide or reference for those engineers and applied scientists working in this field. It can also serve as a text for those currently enrolled in academic curricula concerned with energy and energy-related topics.

The authors hope that this book will place in the hands of academic, industrial, and government personnel – including policymakers and energy resource/management planners – a book that covers the fundamental principles and applications of hydrogen energy thoroughly and clearly. The authors further hope that, on completion of the text, readers will have acquired not only a working knowledge of hydrogen energy, but also experience in their application; and, that they will find themselves approaching advanced texts, engineering and science literature, and industrial applications (even unique ones) with more confidence.

Last, but not least, the authors believe that this modest work will help the majority of individuals working and/or studying in the field of hydrogen energy to obtain a more complete understanding of this subject matter. If you have come this far and read through this Preface, you have more than just a passing interest in this subject. We strongly recommend that you take advantage of the material available in this book. We think it will be a worthwhile experience.

Smithfield, Utah, October 2024

Vincent J. DelGatto
Louis Theodore
R. Ryan Dupont
Matthew C. Ogwu

Part I

Energy Overview

The first part of the book provides a broad overview of energy issues, resources, policies, and regulatory considerations, and includes a glossary of some important terms. The chapters are organized as presented below.

Chapters

1) Glossary of Key Energy Terms
2) Introduction to Energy and Energy Issues
3) Energy Resources
4) Environmental Policy and Regulatory Considerations for Hydrogen Energy
5) Thermodynamic Considerations
6) Fuel Cells

Those readers solely interested in hydrogen energy and hydrogen energy issues may choose to bypass Part I and proceed directly to Part II.

Hydrogen Energy: Principles and Applications, First Edition. Vincent J. DelGatto, Louis Theodore, R. Ryan Dupont, and Matthew C. Ogwu.

1

Glossary of Key Energy Terms

1.1 Introduction

This first chapter of the book provides the definition of hundreds of terms in use throughout the energy field, particularly as they apply to hydrogen. As one might suppose, the reader is primarily introduced to energy and energy-related terms. As noted in the Preface, this book is concerned with hydrogen energy and as such, this chapter primarily addresses terms related to this topic. Thus, this chapter may be used whenever and wherever information is needed about words and/or terms in the hydrogen energy field.

Some additional points regarding this glossary that deserve mention are presented below:

1) Each definition is presented in nontechnical jargon.
2) Where necessary, common scientific and engineering units have been included.
3) A conscious attempt was made to only include terms that are often used in practice.
4) Only one spelling is used for words with multiple accepted spellings but with shared meaning.
5) Different terms with the same meaning are cross-referenced by using the wording "see also".
6) Important acronyms are also included in the chapter.

This chapter defines many but not all of the terms that the reader will encounter in this book. The following list is therefore not exhaustive as a complete index of the book or glossary of all the terms that appear in the energy field. Finally, the purpose of this chapter is to explain the meanings of technical terms that may be unfamiliar to the reader. Definitions given here are for the purposes of this text and are not necessarily complete or exhaustive. Words or phrases included here are those for which there may be some confusion as to the meaning intended.

Section titles for this energy glossary chapter are presented below:

1.1 Introduction
1.2 Importance of Energy Literacy
1.3 Glossary
1.4 Symbols and Acronyms
References

Hydrogen Energy: Principles and Applications, First Edition. Vincent J. DelGatto, Louis Theodore, R. Ryan Dupont, and Matthew C. Ogwu.

1.2 Importance of Energy Literacy

Why a glossary chapter? A good question. The answer? For some readers, this chapter might be the most important one in the book. Understanding energy and energy-related words and terms can motivate some individuals and prepare others to understand the roles (sustainable) energy plays in their lives. Hence, some people will refer to this chapter as "energy literature" of sorts. Informed individuals on energy topics:

1) Can trace energy flow and flow patterns and think in terms of energy systems and sustainability.
2) Know about their energy usage in terms of the amounts, for what, and where that energy originates from.
3) Can purposefully assess the credibility of energy information, regulations, and policies and decisions about sustainable energy futures.
4) Can communicate generally about energy sources and usage in meaningful ways.
5) Can make informed energy-related decisions based on an understanding of impacts and consequences.
6) Continues to learn about energy.

Thus, energy-related understanding can also help:

1) Lead to more informed decisions
2) Improve the security of a nation
3) Promote economic development
4) Lead to sustainable energy use
5) Reduce environmental risks and negative impacts
6) Help individuals and organizations save/make money

Without this information, individuals and communities will have difficulty making informed decisions on topics including sustainable or smart energy use at home, consumer choices, and national and international energy regulations and policies. Energy education should begin with basic energy literacy connected with the most frequently used terminologies.

Finally, the bulk of the material in this chapter was drawn from the earlier work of Theodore, Reynolds, and Morris (1997), as well as others (Holmes, Singh, and Theodore 1993; Theodore, Ricci and VanVlet 2007; Skipka and Theodore 2014; Dupont, Ganesan, and Theodore 2016; Theodore and Theodore 2021).

1.3 Glossary

- **Above ground tank** – any tank or other container, the volume of which is completely above the plane of the adjacent surrounding surface, and whose surface can be visually inspected.
- **Absolute humidity** – the amount of water vapor present in a unit mass of air, usually expressed in kilograms of water vapor per kilogram of dry air or pounds of water vapor per pound of dry air.
- **Absolute pressure** – the actual pressure exerted on a surface that is measured relative to zero pressure; it equals the gauge pressure plus the atmospheric pressure.
- **Absolute temperature** – the temperature expressed in Kelvin (K) or degrees Rankine (°R).
- **Absolute temperature scale –** a scale (e.g., K, °R) in which temperatures are measured relative to absolute zero.

- **Absolute vacuum** – a void that is completely empty of matter.
- **Absolute zero** – the temperature of zero on either the Kelvin or Rankine scale at which molecular motion is thought to cease.
- **Absorbate** – a substance that is taken up and retained by an absorbent.
- **Absorbent** –any substance that takes in or absorbs other substances.
- **Absorber** – a device in which a gas is absorbed by contact with a liquid.
- **Absorption** – the process in which one material (the absorbent) takes up and retains another (the absorbate) to form a homogenous solution; it often involves the use of a liquid to remove certain gas components from a gaseous mixture.
- **Absorption tower** –a vertical tube in which a rising gas is partially absorbed by a liquid in the form of falling droplets.
- **Acceleration** – the rate of change of velocity with time, ft/s^2.
- **Acceleration due to gravity** – the acceleration of a free-falling body in a vacuum under the influence of gravity; on Earth, this value is taken as $32.2\,ft/s^2$ or $9.8\,m/s^2$.
- **Accident** – an unexpected, undesirable event that is caused by the presence of a hazard and adversely affects humans and/or the environment.
- **Accuracy** – the measure of agreement between a measured value and an accepted or true value; it is expressed as the percentage difference between the true and measured values relative to the true value.
- **Acetogen** – a microorganism involved in the anaerobic transformation of organic matter to methane during biogas production.
- **ACFM** – see actual cubic feet per minute.
- **Acid** – a material containing hydrogen that produces at least one hydrogen ion when dissolved in a water solution; it can react with and neutralized by a base to form a sault.
- **Acid dew point** – the dew point of flue gases that contain any significant quantity of sulfur trioxide, SO_3; this temperature is generally 300°F.
- **Activated alumina** – a highly porous, granular form of aluminum oxide with absorptivity for moisture and odor contained in gases and some liquids.
- **Activated carbon** – a highly adsorbent, amorphous form of carbon employed to remove odors, gaseous pollutants, and toxic substances from gaseous emissions or to remove dissolved organic material from wastewater.
- **Activated sludge** – a suspension of aerobic microorganisms with the ability to remove polluting material from a stream of wastewater.
- **Activation energy** – the minimum amount of energy that a molecule must require before it can be regarded as being activated (i.e., able to undergo a reaction).
- **Actual cubic feet per minute (acfm**) – a unit of flow rate measured under actual pressure and temperature conditions.
- **Additives** – specialty chemicals incorporated into fuels and lubricants that enhance the performance of the finished product.
- **Adiabatic** – a term used to describe a system in which no gain or loss of heat is allowed to occur.
- **Adiabatic flame temperature** – the maximum temperature that a combustion system can reach.
- **Adiabatic process** – a process in which there is no transfer of heat across the system boundary.
- **Adiabatic temperature** – the temperature attained by a reaction undergoing a volume or pressure change in which no heat enters or leaves the system.
- **Adsorbent** – a substance (e.g., activated carbon, activated alumina and silica gel) that can condense or hold molecules of other substances on its surface.
- **Adsorber** – an apparatus in which molecules of gas or liquid are captured by a solid.

- **Adsorption** – the physical or chemical bonding of molecules of gas, liquid, or dissolved solid to the external or internal (if porous) surface of a solid; it is an advanced method of treating waste that is employed to remove odor, color, or organic matter from a system.
- **Advanced wastewater treatment** – any process that is employed for the treatment of wastewater that follows other physical, chemical, or biological treatment and serves to improve the quality of effluent prior to reuse or discharge; this includes charged helium nucleus
- nutrients, suspended solids, nonbiodegradable organics, etc.
- **Aerobic digestion** – the breakdown of suspended and dissolved organic matter in the presence of oxygen.
- **Afterburner** – a secondary burner, located so that combustion gases from the primary incinerator are further burned to remove smoke, odors, and other pollutants.
- **Agent** – a biological, physical, or chemical entity capable of causing disease.
- **Agglomeration** – the process by which smaller particles grow larger by collision or contact with other particles.
- **Air heater** – a heater exchanger through which air passes and is heated or cooled by a medium at a different temperature.
- **Air preheater** – an air heater that increases the temperature of an air stream entering a process.
- **Air quality** – the degree of cleanness of the air with regard to lack of pollution.
- **Aliphatic** – one of the major groups of organic compounds characterized by straight or branched chain arrangement of constituent carbon atoms; they are divided into alkanes, alkenes, or branched compounds.
- **Alkali** – any basic substance that is bitter in water solution and irritating or caustic to the skin and mucous membranes; it turns litmus blue, has a pH value greater than 7.0, and is typically employed in wastewater treatment processes.
- **Alkaline electrolyzer** – the oldest technology for creating hydrogen from water and electricity.
- **Alkaline fuel cell** – one of the oldest and cheapest fuel cell technologies that is highly conductive of electrolyte and highly reactive to electrodes.
- **Alkalinity** – a measure of the degree of reaction by a compound with hydrogen ions (e.g., the capacity of water to neutralize acids).
- **Alkane** – a member of a series of saturated, aliphatic hydrocarbons.
- **Alkene** – a member of a series of unsaturated, aliphatic hydrocarbons that are characterized by double bonds between carbon atoms.
- **Alkyl** – a paraffinic hydrocarbon group that may be derived from an alkane by removing one hydrogen from the molecule.
- **Alkylation** – a process in which a high-octane blending component for gasoline is derived from catalytic combination of an isoparaffin and an olefin.
- **Alpha (α) particle** – a positivelycharged helium nucleus (i.e., two protons and two neutrons) that is emitted spontaneously from radioactive elements.
- **Ambient temperature** – the temperature of the surrounding air.
- **Amine** – a class of organic compounds of nitrogen that may be derived from ammonia (NH_3) by replacing one or more of the hydrogen atoms with an alkyl group.
- **Ammonia (NH_3)** – the different directions fifth highest volume of chemical produced in the United States that exists as a colorless gas or liquid with a sharp, intensely irritating odor; the inhalation of concentrated fumes may be fatal, and it has a TLV of 25 ppm in air and explosive limits of 16–25% in air.
- **Ampere** – a unit of electrical current, equal to 1 C/s.
- **Amplitude** – the peak, or maximum value, in wave-type transmissions.

- **Anaerobe** – an organism that carries out microbial reactions in the absence of oxygen.
- **Anaerobic digestion** – the degradation of organic matter by anaerobic organisms in the absence of oxygen to produce primarily carbon dioxide and methane.
- **Ancillary equipment** – any secondary equipment or device including piping, fittings, valves, pumps, etc.
- **Anhydrous** – an inorganic compound that does not contain water, either adsorbed on its surface or combined as water of crystallization.
- **Anion** – a negatively charged ion.
- **Anisotropic** – a term used to describe a material with different optical or other physical properties in different directions (e.g., quartz an graphite).
- **Annual energy production (AEP) –** the energy generated by turbine(s) over the course of 1 year.
- **Anode** – the positive electrode of an electrolytic cell to which negatively charged ions travel when an electric current passed through the cell.
- **Anticipated transient without scram (ATWS) –** for a nuclear reactor, an accident for which the initiating event is an anticipated operational occurrence and in which the system for fast shutdown of the reactor fails to function.
- **Applicant –** any person or organization applying to a regulatory body for authorization (or approval) to undertake specified activities.
- **Approval –** the granting of consent usually by a regulatory *body*.
- **Aqua** – a term used to designate water such as in a stream, a lake, or other sources.
- **Aqueous solution** – any solution dissolved in water.
- **Archimedes' principle** – the principle that the buoyant force on an object immersed in a fluid is equal to the weight of fluid displaced by it.
- **Aromatic** – a term used to describe a major group of unsaturated cyclic hydrocarbons containing one or more rings, typified by benzene which has a six-carbon ring containing three double bonds.
- **Arrangements (for operations) –** the integrated set of infrastructural elements necessary to provide the capability for performing a specified function or task required to carry out a specified operation.
- **Assessment** – the process, and the result, of analyzing systematically and evaluating the hazards and problems associated with sources and practices, and associated protection and safety measures for the purposes of protecting the public and environment against risks.
- **Atmosphere** – the gaseous envelope of fluid surrounding the Earth that comprises the troposphere, stratosphere, mesosphere, and thermosphere; the Earth's atmosphere consists of 79.1% nitrogen, 20.9% oxygen, about 0.03% carbon dioxide, a trace of the noble gases, water vapor, and traces of ammonia, organic matter, ozone, various salts, and suspended solid particles.
- **Atmospheric dispersion** – the mechanism of dilution of smoke or gaseous pollution in which the concentration is progressively decreased.
- **Atmospheric pressure** – the pressure exerted by the atmosphere at any given point.
- **Atmospheric stagnation** – the condition of very little or no air movement.
- **Atom** – the smallest unit of an element that retains all the properties of the element; it is composed of electrons, neutrons, and protons.
- **Atomic energy** – the energy, in the form of heat and radiation, that is derived in a controlled fashion from nuclear fission or fusion.
- **Atomic fission** – the breaking down of large atoms into smaller atoms or elements, involving the liberation of heat, gamma rays, alpha particles, and beta particles.

- **Atomic mass unit (amu)** – a unit equal to one-twelfth the mass of one neutral C^{12} atom.
- **Atomic weight** – the average weight or mass of all the isotopes of an element as determined by the proportion in which they are present in a given element; it is based on the mass of isotopes of carbon which is assigned a reference value of 12.000.
- **Attenuation –** the reduction in intensity of radiation passing through matter due to processes such as absorption and scattering.
- **Authorization** – the granting by a regulatory body or other governmental body of written permission for a person or organization to conduct specified activities. Authorization could include licensing (issuing a license), certification (issuing a certificate), or registration.
- **Autogenous combustion** – any burning without the addition of supplementary fuel.
- **Autoignition** – the starting of a fire without the addition of an external source such as a flame, spark, or heat.
- **Autoignition temperature (AIT)** – the temperature to which a closed or nearly closed container must be heated so that a flammable liquid, when introduced into the container, will ignite spontaneously or burn without the presence of a spark or flame.
- **Automatic control** – the maintenance of desired process conditions by means of sensing devices.
- **Available hydrogen** – naturally occurring liquid, gaseous, or solid hydrogen (or deuterium or tritium) on Earth often in combination with oxygen, carbon, or other elements.
- **Available oxygen** – the quantity of dissolved oxygen available for oxidation of organic matter.
- **Avogadro's number** – the number ofmolecules in 1 mol of a substance, 6.23×10^{23}.
- **Baffle** – a flow-regulating device consisting of a perforated metal plate placed horizontally to restrict or divert the passage of a fluid, usually used for the purpose of providing a uniformly dispersed flow.
- **Ball joint** – a flexible pipe joint formed in the shape of a ball or sphere.
- **Ball valve** – a nonreturn valve consisting of a ball resting on a cylindrical seat within a fluid passageway or pipe.
- **Barometric pressure** – the pressure of the ambient air in the atmosphere at a particular point or above the surface of the Earth.
- **Barrels of oil equivalent –** a unit of measure to quantify crude oil, natural gas liquids, and natural gas amounts using the same basis.
- **Base** – any compound that dissociates in an aqueous solution to yield hydroxyl ions; it is employed to neutralize acids.
- **Baseload** – the minimum level of demand on an electrical grid over a given period of time (usually over the year, or over a season or day); base load power sources are power stations that are capable of consistently generating the electrical power needed to cover this demand.
- **Baseload generation –** electric generation units that typically run all 24 hours a day.
- **Basic** – a term used to describe a compound that is alkaline, i.e., has a pH greater than 7.0.
- **Batch process** – a process that is not continuous; its operations are carried out with discrete quantities of material.
- **Battery** – a device consisting of one or more electrically connected electrochemical cells that is designed to receive, store, and deliver electric energy; it converts chemical energy to electrical energy.
- **Bernoulli's theorem** – a physical law of hydraulics that states that the energy per mass is constant at any point in a conduit; this energy comprises a velocity head, a pressure head, and a static head.
- **Beta (β) particle** – a charged particle emitted from a radioactive atomic nucleus; it has moderate penetrative power and can damage living tissue.