



## Recent developments in state-of-the-art hydrogen energy technologies – Review of hydrogen storage materials

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### ARTICLE INFO

**Keywords:**  
Hydrogen energy technologies  
Hydrogen storage  
Metal hydrides  
Carbonaceous  
Nanoparticles  
Metal organic frameworks  
Perovskites  
Fuel cells

### ABSTRACT

Hydrogen energy has been assessed as a clean and renewable energy source for future energy demand. For harnessing hydrogen energy to its fullest potential, storage is a key parameter. It is well known that important hydrogen storage characteristics are operating pressure-temperature of hydrogen, hydrogen storage capacity, hydrogen absorption-desorption kinetics and heat transfer in the hydride bed. Each application needs specific properties. Every class of hydrogen storage materials has a different set of hydrogenation characteristics. Hence, it is required to understand the properties of all hydrogen storage materials. The present review is focused on the state-of-the-art hydrogen storage materials including metal hydrides, magnesium-based materials, complex hydride systems, carbonaceous materials, metal organic frameworks, perovskites and materials and processes based on artificial intelligence. In each category of materials' discovery, hydrogen storage mechanism and reaction, crystal structure and recent progress have been discussed in detail. Together with the fundamental synthesis process, latest techniques of material tailoring like nanostructuring, nanoconfinement, catalyzing, alloying and functionalization have also been discussed. Hydrogen energy research has a promising potential to replace fossil fuels from energy uses, especially from automobile sector. In this context, efforts initiated worldwide for clean hydrogen production and its use via fuel cell in vehicles is much awaiting steps towards sustainable energy demand.

**Abbreviations:** IEA, International Energy Agency; CEM, Clean Energy Ministerial; MI, Mission Innovation; MT, Million Tons; IRENA, International Renewable Energy Agency; AEO, Annual Energy Outlook; US-DOE, United States Department of Energy; LCOE, Levelized Cost of Electricity; SMR, Steam Methane Reforming; kWh, Kilo Watt-hour; MOF, Metal Organic Frameworks; PCTO, Fuel Cell Technologies Office; AI, Artificial Intelligence; ML, Machine Learning; SWCNT, Single Wall Carbon Nanotube; MWCNT, Multiwall Carbon Nanotube; ANI, Artificial Narrow Intelligence; AGE, Artificial General Intelligence; HSA, Hydrogen Storage Alloys; IMC, Intermetallic Compounds; Pa, Pascal; MPa, Mega Pascals; Atm, Atmosphere; BCC, Body Centered Cubic; SS, Solid Solution; Ni-MH, Nickel-Metal Hydride; P-C-T (or PCT), Pressure Composition Temperature; Wt% (or wt%), weight percentage; kJ, Kilo Joules; PEM, Proton Exchange Membrane; H<sub>2</sub>/M, Hydrogen to metal ratio; CRMM, Controlled Reactive Mechanical Milling; HRMM, High-Energy Ball Milling; NPs, Nanoparticles; PMMA, Poly(methyl methacrylate); CA, Carbon Aerogels; 2D and 3D, Two and Three Dimension; DFT, Density Functional Theory; RHC, Reactive Hydride Composite; K, Kelvin (Temperature scale); °C (or °C), Degree Celsius (Temperature scale); CC, Covalent Crystals; LOHC, Liquid Organic Hydrogen Carriers; MWNT, Multiwall Nanotubes; GPa, GigaPascals; TM, Transition Metal; H-H, Hydrogen-Hydrogen; FCEV, Fuel Cell Electric Vehicle.

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<https://doi.org/10.1016/j.solcom.2023.100033>

Received 7 December 2022; Received in revised form 23 January 2023; Accepted 25 January 2023

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# Recent Developments In Hydrogen Technology

**Anil Kumar Sarma,Uplabdh Tyagi**



## **Recent Developments In Hydrogen Technology:**

**Recent developments in hydrogen technology** Kenneth D. Williamson, 1986      **Advances in Cryogenic Engineering** Peter Kittel, 2012-12-06 The Albuquerque Convention Center was the venue for the 1993 Cryogenic Engineering Conference. The meeting was held jointly with the International Cryogenic Materials Conference. Walter F. Stewart of Los Alamos National Laboratory was conference chairman. Albuquerque is near Los Alamos National Laboratory which has been a significant contributor to the cryogenics community since the early days of the Manhattan Project. Albuquerque is also the home of the Air Force's Phillips Laboratory which has a lead role in developing cryocoolers. The program consisted of 322 CEC papers, more than a 30% increase from CEC 91 and 20% more than CEC 89. This was the largest number of papers ever submitted to the CEC. Of these 249 papers, 193 are published here in Volume 39 of *Advances in Cryogenic Engineering*. Once again, the volume is published in two books. This volume includes a cumulative index for the CEC volumes from 1975-1993, volumes 21, 23, 25, 27, 29, 31, 33, 35, 37, and 39 of *Advances in Cryogenic Engineering*. The first 20 volumes are indexed in Volume 20. A companion cumulative index for the ICMC volumes, volumes 22 through 40, appears in Volume 40. This is my first volume as editor. I would not have been able to have done it without the assistance of the many reviewers. Especially appreciated was the instruction manual left me by the previous editor, Ron Fast.      **Recent Developments in Hydrogen Technology** - Williamson Jr. K.D. Ed., 1986      *Recent Trends in Electrochemical Science and Technology* U. Kamachi Mudali, S. T. Aruna, H. P. Nagaswarupa, Dinesh Rangappa, 2022-04-02 This book encompasses select proceedings of NSEST 2020 and ECSIRM 2020. The volume covers advances in major areas of electrochemical science and technology and surface engineering. It covers all aspects of electrochemistry with more emphasis on corrosion. The corrosion topics include self-healing sol-gel based corrosion-resistant coatings, nitric acid corrosion of stainless steel, stress corrosion cracking, etc. Few chapters are focused on electrodeposition and new materials for oxygen evolution, catalysts, fuel cells, and batteries. The chapters on molecularly imprinted polymer sensor for dual analytes, electrochemical sensors for lead ions, and dopamine, etc., are of interest. Some papers are related to the green synthesis of nanosized oxides and superhydrophobic coatings. This book will be handy and beneficial to researchers, students, and professionals working in areas related to electrochemistry and surface engineering.      *Recent Developments in Hydrogen Technology*, 1986      *Recent Developments in Fusion Energy Research* United States. Congress. House. Committee on Science, Space, and Technology, 1989      *Recent Development in Energy Conversion Systems* Sunday Olayinka Oyedepo, Fidelis Ibiang Abam, Olusegun David Samuel, Oluseyi Olanrewaju Ajayi, Abimbola Patricia Popoola, Diana-Andra Borca-Tasciuc, 2024-03-15 In this industrial and technological age, energy plays a principal role in sustainable development. This is connected to issues regarding availability, production processes, utilization, and environmental impact. Due to the increased rate of population growth, the energy demand in the entire world is getting to the level that it may not be sustained in the nearest future if drastic action is not taken to address

the situation especially from research and development perspectives None of the millennium development goals MDGs can be completed without considerable improvements in the quality and quantity of energy services in developing countries according to the United Nations Development Programme UNDP Based on this fact UNDP is making efforts especially in developing countries to ensure that people have access to sustainable sources of clean reliable and affordable energy since every aspect of human development is highly impacted by this vital resource

**Recent Developments in Green Finance, Green Growth and Carbon Neutrality** Muhammad Shahbaz,Kangyin Dong,Daniel Balsalobre-Lorente,Ayfer Gedikli,2023-08-18 Recent Developments in Green Finance Green Growth and Carbon Neutrality explains the role of green finance in transforming the global economy into a green and carbon neutral one The book explores the synergy between green growth strategy and green finance policy 2G and carbon neutrality in an economic environmental financial framework that helps readers understand how to design a feasible path toward achieving carbon neutrality through economic initiatives and financial innovations It shows how to apply the notion of green growth to organizations and illustrates the need for a theory of energy economics that estimates the benefits of a low carbon transition and carbon neutrality Sections include historical background relevant literature necessary to understand topics the notions of green finance green growth and carbon neutrality from an economic perspective Other sections cover models and methods of carbon neutrality assessment the nexus between carbon neutrality and economic development green growth and financial development green finance and green energy exploration and consumption and more Two chapters specifically focused on UN SDGs 7 and 13 round out the book and it concludes with a final section that gathers and integrates the concepts discussed throughout the book Uses green finance and green growth to develop a framework for achieving a carbon neutral society Brings together current knowledge in this field of research then goes further to explain relevant concepts and the theoretical and empirical relationship between carbon neutrality green growth and green finance Includes two chapters dedicated to a discussion of the United Nations Sustainable Development Goals 7 and 13 which underpin this book

Energy Abstracts for Policy Analysis ,1987 *Recent Developments in Hydrogen Technology* - Williamson Jr KD Ed,1986

**Recent Trends in Thermal Engineering** L. M. Das,Abhishek Sharma,Fitwi Yohaness Hagos,Sumit Tiwari,2021-09-15 This book presents select proceedings of the 3rd International Conference on Computational and Experimental Methods in Mechanical Engineering ICCEMME 2021 It gives an overview of recent developments in the field of fluid dynamics and thermal engineering Topics covered include case studies in thermal engineering combustion engines computational fluid dynamics cfd cooling systems energy conservation energy conversion renewable energy bio fuels gas turbines heat exchangers and heat transfer systems heat pipes and pumps heat transfer augmentation refrigeration and HVAC systems fluids engineering energy and process and thermal power plants The book will be useful for researchers and professionals working in the area of thermal engineering and allied fields

**Aviation Law: Recent Developments In Aviation Laws** Gazala Noor,2024-09-17 Aviation law is a rapidly evolving field

that addresses the regulatory operational and safety aspects of the aviation industry Recent Developments in Aviation Laws provides an in depth analysis of the latest changes and trends shaping this crucial area This book explores significant regulatory updates introduced by international bodies like the International Civil Aviation Organization ICAO and national aviation authorities aimed at enhancing safety security and environmental sustainability The book examines how aviation law is adapting to these changes ensuring the safe integration of new technologies into airspace Recent international agreements and national regulations reflect this shift aiming to make aviation more eco friendly The book also delves into passenger rights highlighting recent enhancements in compensation for delays disability accommodations and data privacy protections Globalization and international agreements continue to shape the legal landscape emphasizing the need for cooperation and harmonization of regulations across borders Recent Developments in Aviation Laws is an essential resource for legal professionals industry stakeholders and policymakers offering comprehensive insights into the current and future state of aviation law

**Recent Developments in Energy and Environmental Engineering** Rafid Al Khaddar,S. K. Singh,N. D. Kaushika,R. K. Tomar,S. K. Jain,2023-06-19 This book comprises select proceedings of the International Conference on Trends and Recent Advances in Civil Engineering TRACE 2022 It discusses the latest topics related to energy and environmental engineering The topics covered include green and clean technologies zero energy buildings solar energy energy conservation and heat recovery solar architecture artificial intelligence for sustainable buildings climate change and plastic and air pollution This book is useful for researchers and professionals working in the area of civil engineering and energy and environmental engineering *Advances in Cryogenic Engineering* R.W. Fast,2012-12-06 Proceedings of the 1991 Cryogenic Engineering Conference held in Huntsville Alabama June 11 14 1991 Fuels and Energy Anil Kumar Sarma,Uplabdh Tyagi,2025-03-03 Human civilization has long relied on fire from biomass for energy Burning an oxidation reaction liberates energy and continues until the material reaches its highest oxidation state The evolution of energy sources from forest fires to nuclear fuels marks significant progress Understanding fuel types and classifications is essential for students and educators This book covers upstream and downstream processing of various fuels biomass petroleum coal natural gas nuclear fuels hydrogen and fuel cells along with combustion technology for energy extraction It also addresses recent advances emission concerns from energy industries and stubble burning The book explores how advanced formulations of coal petroleum and alternative fuels can be optimized for existing combustion systems ensuring efficiency and compliance with EURO VI emission norms This comprehensive guide aims to inform readers about fuel classification energy production and future research prospects

**Recent Developments in Functional Materials for Artificial Photosynthesis** Srabanti Ghosh,Qian Wang,2023-03-08 Artificial photosynthesis is the process of converting solar energy into useful fuels and represents a significant achievement in the production of clean energy for the planet In the process energy is generated from water and CO<sub>2</sub> reduction using solar powered photocatalysis This book provides a comprehensive

overview of recently developed multifunctional materials as visible light driven catalysts their mechanisms and applications in solar energy utilisation and conversion Chapters highlight the use of different approaches such as molecular catalysis nanomaterials systems as well as thin films for solar driven evolution of renewable fuels such as hydrogen This is the first book to give an overview of this area with chapters specifically interesting for those looking towards industrial applications With in depth discussions ranging from understanding to engineering of materials and applied devices it will be suitable for industry professionals researchers and students interested in understanding of the current state of photocatalysis research and its possible applications in the energy domain

**Biohydrogen Production: Sustainability of Current Technology and Future Perspective**

Anoop Singh,Dheeraj Rathore,2016-08-22 Increase in green renewable and sustainable energy demand due to higher environmental impacts e g Greenhouse gases emissions climate change etc on consumption of fossil fuel resource put down an extra pressure on government researchers and industrialists Among several available biofuel options biohydrogen is considered as one of the best environmentally clean fuel and a strong candidate to fulfil the future demand of sustainable energy resource Although biohydrogen production technology and its use as a fuel is still in infancy stage Selection of most sustainable production pathway increase in production upto industrial scale and cost efficiency are some issue still persist with the biohydrogen research Biohydrogen Production Sustainability of Current Technology and Future Perspective is giving an insight for the sustainable production of biohydrogen at industrial scale The process of biohydrogen production is complex and to opt the best suited production system for industrial scale is a frantic task This book will provide an in depth information on all available technologies for biohydrogen production and feedstock options to choose upon This book is also providing information on present status of the research in the field and possibility to change future fuel economy in to biohydrogen economy Experts views provided in the chapters by renowned researchers from all over the globe in the field of biohydrogen research made this book a cornucopia of present research and future perspective of biohydrogen This book is targeted at the researchers working on biohydrogen as well as the bioenergy scientist planning to move towards biohydrogen research This book will provide a platform for motivation of researchers and industrialists for innovative ideas and thoughts to bring biohydrogen production at industrial scale

Advances in Refining Catalysis Deniz Uner,2017-03-16 To meet changing market demands that have stringent emission standards and to ensure proper performance in refinery units evaluation of novel catalyst designs and results from material characterization and testing of catalysts are of crucial importance for refiners as well as for catalyst manufacturers This book highlights recent developments in the application of refinery catalysts in selected units such as fluid catalytic cracking FCC hydrogen production for hydroprocessing units hydrotreating hydrocracking and sustainable processing of biomass into biofuels

Recent Trends in Fuel Cell Science and Technology S. Basu,2007-10-20 Fuel cell science and technology is evolving fast for the past two decades as it is thought to be an efficient way of transforming chemical energy of hydrogen rich compounds

to electrical energy Although this idea of direct conversion of chemical energy to electrical energy was first demonstrated by Sir William Grove in 1839 using a fuel cell it was only in the middle of the twentieth century when Bacon s pioneering work led to the use of fuel cell in space missions The interest in commercialization of fuel cell for civilian use has caught up with government organizations and private corporations for the past decade on account of fluctuating oil prices and environmental concerns It is well known that the conventional fossil fuel which is a primary source of gasoline is not going to last more than a hundred years in the face of ever increasing demand in the developed and developing countries Although the reserves of natural gas coal and tar sands may last another two to three hundred years with the current rate of production their conversion is not efficient and pollution free Thus scientists all over the world have taken up fuel cell development work in their quest of solution to the energy crises looming largely on global population This book aims to script the present status of the rapidly developing field of fuel cell science and technology      **Fossil Energy Update ,1976**

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