



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

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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; Am, 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; H₂/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; MWCNT, Multiwall Nanotubes; GPa, GigaPascals; TM, Transition Metal; H-H, Hydrogen-Hydrogen; FCEV, Fuel Cell Electric Vehicle.

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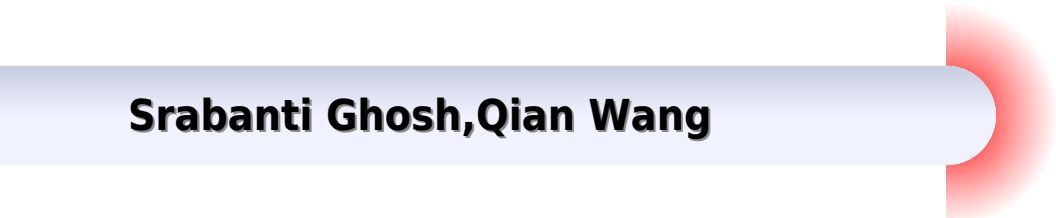
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Recent Developments In Hydrogen Technology

Srabanti Ghosh, Qian Wang



Recent Developments In Hydrogen Technology:

Recent Developments in Hydrogen Technology, 1986 *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 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 Power and Propulsion Applications Ashoke De, Ashwani K. Gupta, Akshai K. Runchal, Dibakar Rakshit, Abhijit Kushari, 2025-09-26 The primary focus of this contributed volume is on providing cutting edge developments in a number of critically important fields including energy combustion power propulsion environment using fossil fuels and the production and use of biofuels The availability of clean and sustainable energy is more crucial now than ever before for all areas of energy use in power mobility and propulsion In the future the energy used will only grow due to the increase in population and enhanced standards of living This book includes contributions from globally recognized specialists from various regions of the world They have provided the most recent advances in both basic and applied research on the creation of cleaner energy and its application for a variety of technologies from microscale energy conversion to supersonic and hypersonic propulsion powered by hydrocarbon fuels Clean and efficient energy conversion for various stationary and propulsion applications including hypersonic propulsion thermal management emission control and environmental issues for energy sustainability are amongst the challenges and opportunities followed for the specific applications In parallel some of the other applications include the combustion of fossil and biofuels clean energy production from low grade materials such as waste and biomass and alternative fuels via rigorous modeling and simulation with a focus on efficiency and environmental issues The present and future R D activities include specially designed technical tracks and contributions from internationally recognized technical experts that reveal different but complementary viewpoints on fuels combustion power and propulsion and air toxins The development and implementation of novel energy conversion technologies require solid fundamental

understanding as well as research and development efforts at different scales from bench to pilot to full scale We conjecture that for the foreseeable future hydrocarbon fuels will likely remain a major source of energy in all sectors of power transportation and propulsion with a slow but steady increase in renewable energy resources in the overall energy mix A multifaceted strategy is needed for the energy and environmental sustainability of all power and propulsion systems This includes creating and utilizing alternative and renewable fuels designing flexible fuel combustion systems that are simple to use with the new fuels and developing cutting edge eco friendly technologies to maximize the use of all types of gas liquid and solid fuels This book provides a wealth of knowledge as a reference for practicing engineers research engineers researchers and managers in labs and industry academic institutions graduate students and senior year undergraduates studying mechanical chemical aerospace energy and environmental and industrial engineering

Recent Developments in Hydrogen Technology - Williamson Jr KD Ed,1986 *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 *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

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

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

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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

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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 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 CO₂ 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 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 **Sustainable Fuel Technologies Handbook** Suman Dutta,Chaudhery Mustansar Hussain,2020-09-25 Sustainable Fuel Technologies Handbook provides a thorough thermodynamic analysis of new and current methods to give detailed insight into energy efficiency processes This book includes the production methods storage systems and applications in various engines as well as the safety related issues associated with all stages of production storage and utilization With a comparison of cost implications and a techno economic evaluation checking the feasibility of sustainable fuel use this handbook is an invaluable reference source for researchers professionals and scientists working in the field of sustainability The present power from solar biomass wind hydrogen and other forms of renewable energy generated from sustainable sources can be harvested by various means and utilized in a variety of industries supporting the need for clean fuels in modern society However there is still limited global availability and insufficient storage which are required for efficient and effective harvesting of sustainable fuels Discusses new and innovative sustainable fuel technologies Provides an integrated approach for modern tools methodologies and indicators in sustainable technologies Evaluates advanced fuel technologies alongside other transformational options *Recent Developments in Atomic Force Microscopy and Raman Spectroscopy for Materials Characterization* Chandra Shakher Pathak,Samir Kumar,2022-01-07 This book contains chapters that describe advanced atomic force microscopy AFM modes and Raman spectroscopy It also provides an in depth understanding of advanced AFM modes and Raman spectroscopy for characterizing various materials This volume is a useful resource for a wide range of readers including scientists engineers graduate students postdoctoral fellows and scientific professionals working in specialized fields such as AFM photovoltaics 2D materials carbon nanotubes nanomaterials and Raman spectroscopy

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