ACBHPE 2022

Workshop on Awareness and Capacity Building in **Hydrogen Production and Energy uses: Towards a Net-Zero strategy (ACBHPE-2022)**

8th - 10th June, 2022, New Delhi, India

Azadi Ka Amrit Mahotsav

Pre-Workshop Bulletin of Lecture Notes

Workshop Highlights

Day 1: Hydrogen Production Technologies

Day 2: Green Hydrogen Production - Hybrid approach

Thermal (coal, gas & oil) Conversion with CCS

Day 3: Sustainable Hydrogen Storage & Energy Uses

Green Chemistry of Hydrogen – biological approach

Hydrogen Startups Ecosystem

Workshop Theme

Chemistry of Hydrogen Production and Energy uses

Organized by

Climate Change Research Institute

In Collaboration With

India International Centre

ONLY ONE EARTH

Awareness and Capacity Building in Hydrogen Production and Energy uses: Towards a Net-Zero Strategy

ACBHPE-2022

PRE-WORKSHOP LECTURE NOTES

Venue

India International Centre Annexe, Lecture Hall 1
June 8 – 10, 2022

Workshop Highlights

08.06.2022	**Hydrogen Production Technologies**
09.06.2022	**Green Hydrogen Production: Hybrid approach**
09.06.2022	**Thermal (coal, oil & gas) Conversion with CCS**
10.06.2022	**Sustainable Hydrogen Storage, Energy Uses & Risk Management**
10.06.2022	**Green Chemistry of Hydrogen: Biological approach**
10.06.2022	**Startups Ecosystem**

Climate Change Research Institute
Science & Technology Solutions for Sustainable Energy Future

Climate Change Research Institute
Science & technology solutions for sustainable energy future

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Date: 4th June, 2022

Foreword

I am happy that Climate Change Research Institute has taken this initiative to conduct a national level workshop as Awareness and Capacity Building Programme on **Hydrogen Production and Energy Uses: Towards a Net-Zero Strategy (ACBHPE-2022)** from June 8th to June 10th, 2022 in collaboration with the India International Centre, Delhi as World Environment Day 2022 celebration.

India's energy is coal dominant at present. In a move towards net-zero strategy, India has set an ambitious programme of renewable energy expansion to achieve 500 GW capacity by 2030. The efforts to clean energy transition in order to meet the climate targets have led to launch of National Hydrogen Energy Mission with the ambition to make India a global hub for Green Hydrogen production and export. The announcement of the Hydrogen Mission during August 2021 amidst celebration of 75th year of *Azadi ka Amrit Mahotsava* and the Green Hydrogen Policy by Ministry of Power in February, 2022 have substantially increased the interest of industry in realizing the potential of hydrogen energy to play a major role in the nation's long-term energy future. A target to achieve 5 million tons of green hydrogen by 2030 has been set.

Green hydrogen is produced from electrolysis of water, when the energy comes from renewable sources like, solar or wind or biomass. There are many challenges & opportunities in the production of Green Hydrogen. Focus efforts are required for cost-effective production of hydrogen by adopting new and innovative ways from variety of sources.

I am confident that the workshop will give the participants, national and international insights about the advancements made in science & technology of hydrogen production technologies and help in progress of implementation of the hydrogen mission.

I wish the ACBHPE-2022 great success.

(Prof. D. P. Agrawal)
Chairman, Governing Council
Climate Change Research Institute
Ex-Chairman, UPSC and Ex-Founder Director, IIITM, Gwalior

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Preface

Post COVID-19 the Climate Change Research Institute has taken an initiative in collaboration with the India International Centre to have the physical event for the World Environment Day 2022 deliberations through participation from the experts and youth. An Awareness and Capacity Building Workshop on **Hydrogen Production and Energy Uses: Towards a Net-Zero Strategy (ACBHPE-2022)**, is being held at IIC Annexe Lecture Hall 1 from June 8th to June 10th, 2022.

In the past 50 years, the world economy has been fossil fuel dominant. As fossil fuel combustion causes high CO_2 emissions with the growing concerns about the onset of climate change emergency the 21st century is becoming catastrophic. Our energy systems are undergoing a transition worldwide and technology for capturing carbon dioxide and its removal from the atmosphere by storage underground or utilization has come up as an option for sustaining fossil fuel use. The other option is the use of renewable resources, which are emission-free.

In this context, solar-rich countries of the world have formed International Solar Alliance (ISA) and are taking steps to achieve ambitious solar energy targets. The Intermittence of solar energy, however, demands its cost-effective storage for uninterrupted use in practical devices. Solar chemical fuels are proving a promising solution and hydrogen is one such fuel that can be produced from solar energy by adopting advanced techniques of artificial photosynthesis.

The workshop, therefore, aims to create awareness not only on the research issues of hydrogen production but also options for cost-effective clean energy uses sustainably. In organizing the ACBHPE – 2022 workshop we had several blissful developments. Prof G. D. Yadav, *Padamshree* Emeritus Professor of Eminence motivated us from the very beginning with his honoured participation. Shri R. V. Shahi, Former Power Secretary inspired us and is presiding over the deliberations. Prof D. P. Agrawal, Chairman National Advisory Board has been a source of strength at every stage. We feel motivated by the overwhelming response from the eminent experts and delegates from various institutions across the country.

It is hoped that the three-day national level workshop will provide a platform for young students and researchers to learn about the scientific & technological challenges faced in hydrogen production and energy uses. We earnestly desire that the workshop deliberations would be serving the goal of implementing the hydrogen mission programme of the Government of India and making progress toward Climate Action.

Dr. (Mrs.) Malti Goel,
Organizing Secretary, ACBHPE-2022
President, Climate Change Research Institute

Climate change Research Institute

WORKSHOP ON AWARENESS AND CAPACITY BUILDING IN HYDROGEN PRODUCTION AND ENERGY USES: TOWARDS A NET-ZERO STRATEGY

ACBHPE-2022

Pre- Workshop Lecture Notes

CONTENTS

‘Why Workshop?

Awareness and Capacity Building in Hydrogen Production and Energy uses: Towards a Net-Zero strategy (ACBHPE- 2022), 8th – 10th June, 2022

Background

- In the meeting of United Nations Conference of Parties (COP 26) held in Glasgow in early November 2021, world leaders have agreed to take intense national and international climate actions in a move towards net-zero emission targets. India as a nation is striving for Green Growth and Climate Justice. The country would become carbon neutral and achieve net zero emissions by the year 2070.

- The announcement of National Hydrogen Mission (NHM) in August 2021 to commence the India’s energy independence journey in the 75th year of Independence as “Azadi Ka Amrit Mahotsav” and Green Hydrogen Policy in February 2022 have substantially increased the interest in realizing the potential for Hydrogen energy to play a major role in the nation’s long-term energy future. Hydrogen energy is currently at a nascent stage of development.

- To examine key technical issues about the hydrogen production and uses, assessment need to be made for the current state of R&D technology and sectoral uses of hydrogen. There is not a single sector of economy which is not affected by the 2070 targets. Topics covered would include the hydrogen end-use technologies, hydrogen production technologies, carbon capture & storage from hydrogen processing and transition issues for hydrogen in the energy sector.

- India is among the few developing countries, which has intensified Hydrogen research funded by the Government viz. DST, CSIR, DAE as well as Industry viz. NTPC, ONGC, Reliance among others. The workshop would provide an exposure to current status for understanding and bridging the gaps.

- It is therefore timely that an exposure is provided about world view on the subject and issues are elaborated for broadening the perspectives for implementation of the Hydrogen policy.

Objectives of the Workshop

The national level workshop is aimed at knowledge dissemination in understanding of issues and challenges in Hydrogen energy for Sustainability. Advancements in science & technology of hydrogen production technologies and energy uses with special reference to India’s Climate Action and National Hydrogen Mission along with start-ups perspectives are proposed to be shared.

Climate change Research Institute

The Climate change Research Institute has been founded with a vision to promote understanding of climate change, mentoring and developing human resources. Over the years CCRI is serving the society and getting recognized nationally and internationally. It is working on the practical grounds to implement the change, through its unparalleled research in the energy sector by adopting practices of science, technology and innovation (STI).

In the biannual workshops held by CCRI so far, there has been huge motivational effect on the work being carried out in various research centers in the country as the participants were exposed to practical utilization of their research for public good. Excellent feedbacks have been received from the participants. Our previous capacity building workshop on Carbon Capture and Utilization has led to a scientific book on 'Climate Change and Green Chemistry of CO2 Utilization' published by Springer Nature under Green Energy and Technology series https://link.springer.com/book/10.1007/978-981-16-0029-6.

Green Hydrogen/ Green Ammonia Policy, Govt. of India

A Major Policy Enabler by Government for production of Green Hydrogen/ Green Ammonia using Renewable sources of energy

A step forward towards National Hydrogen Mission

Posted On: 17 FEB 2022 5:46PM by PIB Delhi

Hon'ble Prime Minister launched the National Hydrogen Mission on India's 75th Independence Day (i.e. 15th August, 2021). The Mission aims to aid the government in meeting its climate targets and making India a green hydrogen hub. This will help in meeting the target of production of 5 million tonnes of Green hydrogen by 2030 and the related development of renewable energy capacity.

Hydrogen and Ammonia are envisaged to be the future fuels to replace fossil fuels. Production of these fuels by using power from renewable energy, termed as green hydrogen and green ammonia, is one of the major requirements towards environmentally sustainable energy security of the nation. Government of India is taking various measures to facilitate the transition from fossil fuel / fossil fuel based feed stocks to green hydrogen / green ammonia. The notification of this policy is one of the major steps in this endeavour.

The policy provides as follows:

i. Green Hydrogen / Ammonia manufacturers may purchase renewable power from the power exchange or set up renewable energy capacity themselves or through any other, developer, anywhere.
ii. Open access will be granted within 15 days of receipt of application.

iii. The Green Hydrogen / Ammonia manufacturer can bank his unconsumed renewable power, up to 30 days, with distribution company and take it back when required.

iv. Distribution licensees can also procure and supply Renewable Energy to the manufacturers of Green Hydrogen / Green Ammonia in their States at concessional prices which will only include the cost of procurement, wheeling charges and a small margin as determined by the State Commission.

v. Waiver of inter-state transmission charges for a period of 25 years will be allowed to the manufacturers of Green Hydrogen and Green Ammonia for the projects commissioned before 30th June 2025.

vi. The manufacturers of Green Hydrogen / Ammonia and the renewable energy plant shall be given connectivity to the grid on priority basis to avoid any procedural delays.

vii. The benefit of Renewable Purchase Obligation (RPO) will be granted incentive to the hydrogen/Ammonia manufacturer and the Distribution licensee for consumption of renewable power.

viii. To ensure ease of doing business a single portal for carrying out all the activities including statutory clearances in a time bound manner will be set up by MNRE.

ix. Connectivity, at the generation end and the Green Hydrogen / Green Ammonia manufacturing end, to the ISTS for Renewable Energy capacity set up for the purpose of manufacturing Green Hydrogen / Green Ammonia shall be granted on priority.

x. Manufacturers of Green Hydrogen / Green Ammonia shall be allowed to set up bunkers near Ports for storage of Green Ammonia for export / use by shipping. The land for the storage for this purpose shall be provided by the respective Port Authorities at applicable charges.

The implementation of this Policy will provide clean fuel to the common people of the country. This will reduce dependence on fossil fuel and also reduce crude oil imports. The objective also is for our country to emerge as an export Hub for Green Hydrogen and Green Ammonia.

The policy promotes Renewable Energy (RE) generation as RE will be the basic ingredient in making green hydrogen. This in turn will help in meeting the international commitments for clean energy.

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IN PURSUIT OF THE NET ZERO GOAL & SUSTAINABILITY: ADOPTION OF GREEN HYDROGEN TECHNOLOGIES, CO_2 REFINERIES AND BIOMASS VALORIZATION

***Padamshree* Prof. Ganapati D. Yadav**,
National Science Chair (SERB/GOI)
Emeritus Professor of Eminence
Institute of Chemical Technology, Mumbai-400019

Extended Summary

The leading economies of the world should go for production of green hydrogen in pursuit of the Net Zero goal of the Paris Agreement of 2015. Hydrogen is best suited for converting any biomass and carbon dioxide emanated from different sources, into fuels and chemicals. Hydrogen will also lead, on its own as energy source, to the carbon negative scenario in conjunction with other renewable non-carbon sources such as solar, wind, tidal, geothermal, nuclear or the like. Hydrogenation of biomass leads to many valuable products. So, tomorrow's refineries will be literally carbon dioxide refineries- converting it into hydrocarbons, methanol, dimethyl ether (DME), formic acid, alcohols, syn gas, electricity, hydrogen vehicles, fuel cells, ammonia, and fertilizers, etc. using hydrogen which should be obtained from water splitting. DME is the best replacement for diesel and LPG and the same infrastructure could be utilized. That will lead to carbon-negative economy bringing down the temperature of the globe below 1.5 ^{o}C.

In the ICT Mumbai, we have been conducting research since 2006 on hydrogen production in collaboration with the ONGC Energy Centre (OEC) and achieved tremendous breakthroughs reflected in many international and Indian patents. The cost of hydrogen production by the ICT-OEC Process for Hydrogen is 0.95 USD per kg. The refineries need hydrogen which they produce from steam reforming of natural gas at USD 2 /kg; it is grey hydrogen. The biomass produced hydrogen (blue hydrogen) must convert carbon dioxide into fuels. None of the other technologies patented or otherwise are so lucrative as our technology. We have compared our work with 19 patented technologies. The US DOE predicts cost of hydrogen to be less than 2 USD/kg by 2030 for economically viable and globally competitive. The valorization of the co-product oxygen is not considered in our projections which will bring the cost further down. Our technology is the first of its kind in the world and can meet 70% of energy needs of the country.

Professor Ganapati D. Yadav is one of the topmost, highly prolific, and decorated engineering-scientists in India. He is an Emeritus Professor of Eminence at the Institute of Chemical Technology, Mumbai, India. In March 2022, he was appointed to the prestigious National Science Chair (Mode I) of the Science and Engineering Research Board (SERB) of the Department of Science and Technology (DST) of the Govt. of India and was also elected to the US National Academy of Engineering in February 2022, which are rare honors.

Prof. Yadav is internationally recognized by many prestigious and rare awards as an academician, researcher, and innovator, including his seminal contributions to education, research and innovation in Green Chemistry and Engineering, Catalysis, Chemical Engineering, Energy Engineering, Biotechnology, Nanotechnology, and Development of Clean and Green Technologies. His technology on green hydrogen is highly cost-competitive with cost of less than a dollar per kg and is supported by ONGC for further commercialization. He has made substantial contribution to green and blue hydrogen production, carbon dioxide refineries, biomass valorization, the net zero goal and sustainability. He was conferred Padma Shri, the fourth highest civilian honor, by the President of India in 2016 for his outstanding contributions to science, engineering, and innovation.

Professor Yadav is an elected Fellow of The World Academy of Sciences, Trieste (TWAS), Indian National Science Academy (INSA), Indian Academy of Sciences (IASc), National Academy of Sciences, India (NASI), Indian National Academy of Engineering (INAE). He is a Fellow of Royal Society of Chemistry, UK, Institution of Chemical Engineers, UK, Indian Institute of Chemical Engineers, Indian Chemical Society, and Indian Society for Technical Education, among others. He serves as the President of the Indian Chemical Society, the Maharashtra Academy of Sciences and ACS India International Chemical Sciences Chapter. He also served as the President of the Catalysis Society of India and the Indian Institute of Chemical Engineers. He was the J.C. Bose National Fellow for 10 years.

Since May 2009 to November 2019, he served as the Founding Vice Chancellor (President) and R.T. Mody Distinguished Professor, and Tata Chemicals Darbari Seth Distinguished Professor of Leadership and Innovation at the Institute of Chemical Technology (ICT), Mumbai, which is a Deemed-to-be-University having Elite Status and Centre of Excellence given by State Assembly on par with IITs/IISc/IISERs. He serves as the Adjunct Professor at University of Saskatchewan, Canada, RMIT University, Melbourne, Australia and Conjoint Professor, University of New Castle, Australia. He has been a recipient of two honorary doctorates: D. Sc. (Hon. Causa, DYPU) and D. Eng. (Hon. Causa, NIT Agartala). As the Vice Chancellor he created many records. Under his dynamic leadership, ICT made phenomenal progress having been declared as Category I institute, having started 23 new academic programs, 5 new Departments and several Centers of Excellence, and establishment of two off-campuses in Bhubaneswar with the total support of IndianOil and at Marathwada with the total support of Govt. of Maharashtra, and collected phenomenal funds. The ICT is listed in top 100 institutes in the Developing World by Times Higher Education Ranking in 2019.

He has personally won over 125 national and international honors, awards, fellowships, editorships, and several Life Time Achievement Awards by prestigious industrial organizations. His research productivity is phenomenal with supervision of 107 Doctoral and

135 Masters Theses which is the first record for any engineering professor in India. Besides he has supervised 47 post-doctoral fellows, several summer fellows and research staff. To his credit are 507 original research papers, 115 granted national and PCT patents; 3 books; h-index of 64, i10 index of 317; 15,500+ citations in journals, patents, books and monographs. He was listed in top 2% of the researchers from India in the world in the field of Physical Chemistry and in fact is in top 0.2% with a rank of 66 during 2020 and 2021 and is number 1 in India. He is still actively involved in guiding doctoral students, patenting, publishing, consulting, and transferring technologies to industry. He is on the boards of 5 listed companies as an Independent Director and has been a member or Chair of several policy-making/apex bodies of the Government, Semi-Government organizations and Industries Associations.

GREEN HYDROGEN ECONOMY: CHALLENGES AND OPPORTUNITIES

Prof Prakash C. Ghosh
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Powai, Mumbai-400076

Abstract:

Climate change along with the rapid depletion of fossil fuel, necessitates cleaner energy sources for our fast-growing economy, thus initiating power production from renewable sources of energy. Renewable sources are considered to be the backbone of future sustainable and cleaner energy solutions of the future. One of the significant drawbacks of renewable energy sources is intermittent in nature, and if the energy is not trapped continuously, it is wasted in other forms. Hydrogen is considered as a potential energy carrier for the future to trap renewable energy effectively and efficiently. An overview of the green hydrogen economy will be presented in the proposed lecture, which mainly includes production and utilisation.

Biography

Prakash C Ghosh has been working as an Associate Professor since 2012 in the Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Mumbai, India. Dr. Ghosh received his doctoral degree in Mechanical Engineering from RWTH Aachen, Germany. He is the recipient of BOYSCAST fellowship from DST, Govt. of India and ERASMUS MUNDUS fellowship from the European Union. Dr. Ghosh has worked as a guest scientist in Forschungszentrum Juelich, Germany from 2002 to 2004. He worked in National Chemical Laboratory, Pune, India as a scientist from 2004 to 2006. Dr. Ghosh's research interests include low-temperature fuel cells and electrolyser. In addition, he is also involved in solar hydrogen research. Dr. Ghosh has more than Ninety International Journal papers in the field of energy system hydrogen energy. He has also four awarded international patent and six filed patents in his name. He has participated in several National as well as International projects with several countries such as the United Kingdom, Canada, Australia and the USA in the capacity of Principal Investigator and Co-Principal Investigator. At present, he is leading an Indo-UK project (INR 5.52 Crore) in the field of micro-grid and hybrid energy storage in the capacity of PI, funded by Department of Science and Technology, Ministry of Science and Technology, Govt. of India. He is also leading one of the two Indian consortia for UK-India Joint Virtual Centre for Clean Energy.

HYDROGEN PRODUCTION TECHNOLOGIES AND ENERGY USES

Dr (Mrs.) Malti Goel
President and Chief Executive, CCRI and Former Adviser, DST, Govt. of India

Summary

‘Hydrogen Economy’ refers to use of hydrogen as clean energy source so as to replace the carbon intensive fossil fuels as dominant resources. Hydrogen energy technologies have come in the forefront in the energy sector for two main reasons; a) cost of producing electricity from renewable energy has come down, which suggests green hydrogen can also be produced at lower cost, b) According to IPCCC sixth report with climate change a ‘certainty’ the urgency to mitigate carbon dioxide emissions is becoming a necessity.

India is moving towards hydrogen economy to address concerns for impending climate change and full fill the goals of International Protocols such as Paris Agreement on Climate Change and achievements of Sustainable Development Goals, especially SDG 13 on Climate Action.

Hydrogen is rarely found on earth in free form as a natural resource, though most abundant element in the Universe. Hydrogen production from its various sources on earth are grouped into four categories namely; electrical, thermal, biological and hybrid methods.

(i) Electrical methods - electrolysis and plasma arc dissociation.
(ii) Thermal methods - decomposition of hydrocarbons carried out by gasification and/ or steam reforming of hydrocarbon fuel.
(iii) Biological methods – including biotechnological methods using waste or biomass is a move towards *circular economy*. Levidian Nanosystem in UAE has designed devices for converting the methane gas emitted from landfills or oil producing fields into hydrogen and grapheme, a two dimensional carbon material with unique properties
(iv) Hybrid methods - are combination of one of more processes. There are emerging as promising options specially for obtaining Green hydrogen cost-effectively.

Energy Uses : Hydrogen, the colorless, odourless and invisible gas can have many colors depending on the sources and processes used (Fig. 1).

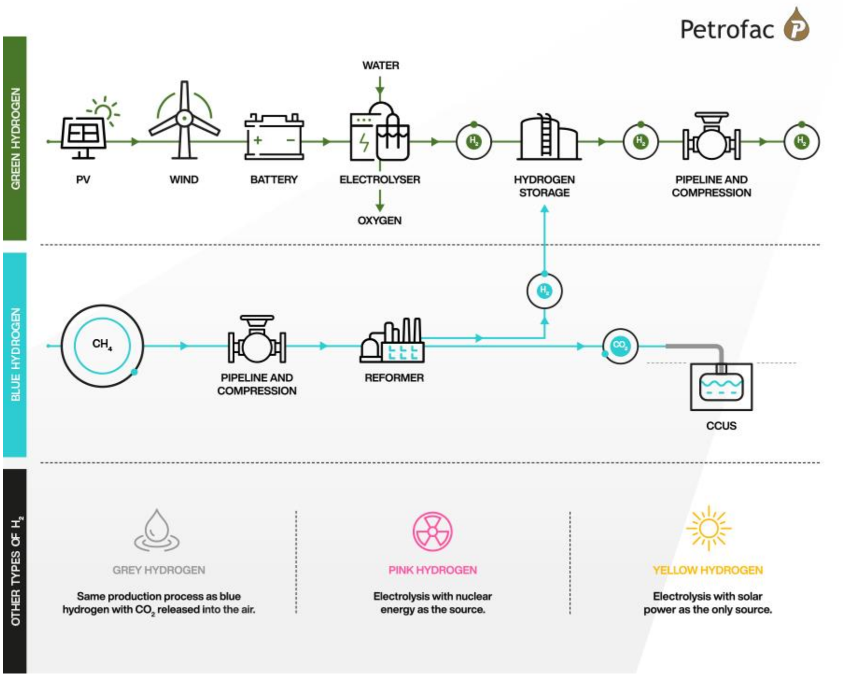
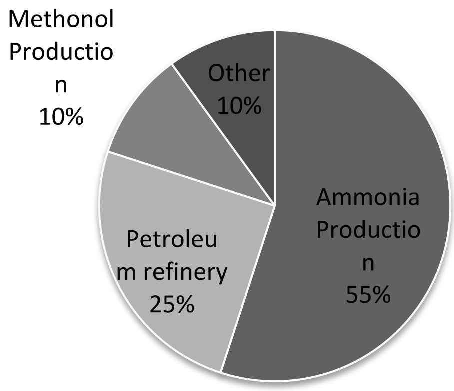


Fig. 1 Hydrogen Production processes

Hydrogen finds major uses in synthetic nitrogen fertilizer industry and petroleum refining and production (Fig.2.). Use of hydrogen as clean fuel in transport and energy industry demands advancements in storage technologies as well as risk management.



Fg. 2 Global share of hydrogen consumption by industry
https://wha-international.com/hydrogen-in-industry/

The *Hindenburg* airship accident of 1937 had raised vital issues and had put airship travel on the back burner, through in road transport advancements since then has made it safer. These issues will be highlighted in the workshop. Examples of major Academia-industry collaborations and Government initiatives in India will be cited.

HYDROGEN PRODUCTION FROM LIQUID HYDROGEN CARRIERS

Dr. Sanjay K. Singh
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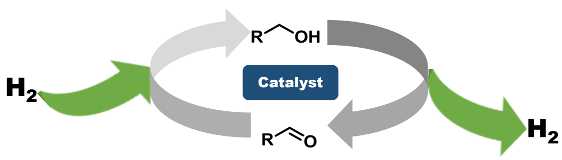
Extended Summary

Hydrogen is the most plentiful element in the universe although the presence of hydrogen as a molecule in the earth's atmosphere is extremely rare (about 1 ppm by volume). One of the major hurdles in exploring hydrogen economy with full potential is the safe production and storage of hydrogen gas. Hydrogen is a clean energy source, and when used in Fuel Cell produces only water as a by-product. However, carrying big and heavy hydrogen cylinders with high pressure has critical safety and economical challenges. Alternatively, using a liquid hydrogen storage material in the fuel tank of existing vehicles (using petroleum products) and generate hydrogen on-board to supply to Fuel Cell is not only a viable concept but is also very economical. In this context, worldwide scientific efforts are concentrated on the liquid organic hydrogen carriers (LOHCs)/Liquid Hydrogen Carriers (LHCs) such as hydrazine monohydrate (8.0 wt% H_2), formic acid (4.4 wt% H_2), formaldehyde (8.4 wt% H_2 $HCHO$-H_2O), and methanol (12.5 wt% H_2), which are not only stable, safe to handle and transport but also release hydrogen under relatively mild conditions in the presence of a suitable catalyst. For instance, Methanol, a C1 alcohol, is a liquid, easy to store, water-soluble fuel, having a large content of H_2 (12.5 wt%) and is being produced on large scale from biomass resources and hydrogen and carbon monoxide, or as industrial by-products. Dehydrogenation of methanol involve three major steps: i) dehydrogenation of methanol generate formaldehyde with the release of one hydrogen molecule, ii) later simultaneous hydration of formaldehyde and dehydrogenation of diol form formic acid with the release of another molecule of hydrogen, and finally iii) dehydrogenation of formic acid releases a molecule of hydrogen along with a molecule of carbon dioxide. Therefore, the intervention of catalysts in tuning the dehydrogenation pathway becomes crucial. This presentation will provide a brief overview of various catalysts and catalytic routes for hydrogen production from liquid organic hydrogen carriers.



HYBRID APPROACHES FOR SOLAR HYDROGEN

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Extended Summary

1.0 Introduction

Solar energy is emerging as the largest source of all energy sources and has untapped capability well beyond its present usage for centralized and decentralized applications. Three broadly classified generic approaches of solar energy conversion systems include solar fuels (including hydrogen methanol etc), PV based solar electricity and solar thermal systems. Amongst the three approaches, solar fuels appears to be a promising approach as it addresses the issue of intermittently availability of sun light due to climatic conditions and day and night cycle. Catalysts that are durable and perform under the harsh conditions of environment in presence of sunlight are needed to catalyze reduction in reaction time and energy requirement to make solar fuels a reality. In this context, the field of plasmonics in solar energy utilization (SUN) is expected to lead to significant improvements in conventional systems and also lead to new and unique applications. Thus development of highly performing selective photocatalysts and plasmonic materials would facilitate development of more efficient devices and system for solar fuels (in specific hydrogen) in photothermal, photothermoelectric, photovoltaic and photocatalytic platforms. The potential of all these approaches of solar energy conversion and storage systems, as well as the potential of hybrid systems have been investigated in our group

Solar hydrogen can be generated in three ways including (1) PV based systems for conversion of solar energy into electricity, which in turn, drives water electrolysis to split water into hydrogen and oxygen ; (2) design of PEC or photocatalytic systems wherein water splitting reactions are driven directly by light, without the need to separately generate electricity; and (3) photothermal systems to provide heat and photons to mixture of water and donor to facilitate photothermal reforming of donor or chemical reactions such as oxidative hydrolysis of zinc etc. Amongst the in-vogue approaches, only PV based water electrolysis is reasonably mature and has the potential to significantly make a mark in the current energy needs and scenario considering the scale of infrastructure already installed. The photocatalytic, PEC and photothermal approaches, hold promise for achieving simplified systems and/or high energy conversion efficiencies, however, they require considerable development for translation of lab scale prototype reactors into pilot-scale and commercially viable systems . The lecture shall briefly provide the status of these three approaches pursued being pursued for artificially producing solar hydrogen. More focused efforts are required to increase the rate of hydrogen generation particularly to address the issue of reducing costs for making the application of solar fuels more meaningful. The following issues and challenges addressed to reduce the large gap between current laboratory demonstrations and deployable technology includes i)Design of broad band absorption material ii)Utilization of low cost donors (preferably waste like sulphides, urea, glycerol) with comparable properties to alcohol for enhancing the net energy recovery iii)Increasing the solar to light efficiency for photocatalytic pure and donor assisted water splitting reaction iv) Enhancing photocatalyst stability v) Reducing cost of the catalyst by replacing or minimizing Pt content vi) Extending device lifetimes vii) Reducing costs and viii) Design of broad band absorption novel reactors for maximizing energy efficiency and minimizing efficiency loss in scale-up systems

2.0 Significant findings at CSIR-NEERI

The solar hydrogen generation approaches pursued includes the following :

(a) Photocatalytic hydrogen generation (30L reactor volume) approach (particulate Donor assisted photocatalytic hydrogen generation system developed)

- **i)** Au-Pt , Cu-Pt and Ag-Pt titania composites developed are showing exemplary HER ranging from 12mmol/h/400ml to 17mmol/h/400ml in presence of donor including methanol, ethanol, glycerol and acetic acid in laboratory– **a unique mechanism of in-situ generated low cost Cl^{-} based donor postulated.**
- **ii)** Pilot plant facility (25 litre reactor volume) established with hydrogen delivery or HER of 380mmol/h in UV-visible illumination -**significantly enhanced HER due to donor and in-situ generated Cl**

(b) Hybrid photothermal pure WS and donor assisted hydrogen generation

- **i)** Au-Pt titania composite showing exemplary HER ranging from 250ml/h /3litre reactor volume to 800 ml/h/3litre reactor volume in presence of ethanol in 10 SUN conditions at temperature of 80-90^{o}C in evacuated reactor in natural sunlight-New finding in donor assisted system in natural sunlight

ii) Au-Pt titania composite showing exemplary HER of 240ml/h/litre reactor volume in presence of ethanol in 10 SUN conditions at temperature of 80-90°C in flat plate reactor in natural sunlight

iii) Oxidative hydrolysis of nano zinc showed HER of 1145 umol/h compared to 300 umol/h for micron sized zinc (recovery through electro deposition shows promising results)

c) Solar PV based water electrolysis (PV-WE) :

Solar PV based water electrolysis essentially includes solar PV for electricity and water electrolyser for generating hydrogen. The approaches being pursued are as follows:

i) Functional PV panel (FPV) developed for skilful photons, thermal and biofilm management which prevents voltage decay& improves shelf life with overall enhancement efficiency of FPV to 22% vis-à-vis 18% for Commercial PV

ii) Facilitated Water electrolyser developed with a) Pt free electrodes b) New concept of donor assisted system for Water electrolyser (WE) c) New redox shuttle (ECPB) identified for spatially separate HER and OER for reducing electricity requirement in WE d) CA enzyme based system showed HER of 1238 umol/h in CO_2 based water splitting reaction system developed - "no organic donor" - new & unreported finding

iii) Compact and modular Integrated PV-WE system fabricated with hydrogen evolution rate (HER) of 4.2L/min and testing in progress for 300W fuel cell

Related Important Publications from the group of Dr Rayalu

(i) Throwing light on Platinized Carbon nano structured composite for hydrogen generation; Energy and Environmental Science, 2014, **7**, 4087-4094;

(ii) Photocatalytic water splitting on Au/TiO_2 nanocomposites synthesized through various routes: Enhancement in photocatalytic activity due to SPR effect; **,** Applied Catalysis B; Environmental 142, 684-693, 2013

(iii) Nano-ferrites for water splitting: unprecedented high photocatalytic hydrogen production under visible light;; Nanoscale

(iv) Orthorhombic/cubic Cd2So4 Nanojunctions: enhancing solar water splitting efficiency by the suppression of charge recombination;**,** Journal of Materials Chemistry; A 2 (2), 492-499., 2014.

(v) Synthesis of Ni2P/CdS and Pt/TiO_2 nanocomposite for photoreduction of CO_2 into methanol, Scientific Reports, Nature group 8084 (2021). https://doi.org/10.1038/s41598-021-87625-w;

2D-NMs PHOTOCATALYSTHYDROGEN EVOLUTION

Dr. Shamim Ahmad
Jamia Hamdard, New Delhi

Extended Summary

CLIMATE CHANGE – MAJOR PROBLEMS Mitigating CO2 Emission & Renewable FUEL
Reduce CO2 Emissions Conversion into Fuels/Chemicals, Produce H2 - Photocatalytic Conversion Efficient & Affordable Photocatalysts A Necessary – Development

Why Hydrogen Fuel?

S. No.	Fuel	MJ/Kg
1.	Liquid Hydrogen	130
2.	Aviation Gasoline	46.8
3.	Premium Gasoline/Petrol	46
4.	Regular Gasoline/Petrol	47
5.	Jet Fuel (Kerosene)	47
6.	Jet Fuel (Naphtha)	46.6
7.	Diesel	48
8.	Biodiesel	39.9
9.	Liquefied Natural Gas	55
10.	E85 (85:15:: ethanol : gasoline)	~33
11.	Ethanol	31.1
12.	Methanol	19.9
13.	Vegetable Oil	37.7
14.	Gasohol (10:90:: ethanol : gasoline)	~45
15.	Liquid Petroleum Gas (LPG)	~51

Exploring 2D-Nanomaterials?

Adjustable Charge Carrier Transport Carrier Lifetime…

Optimal Photocatalyst

Appropriate Band-Gap Semiconductor Right Positioning – CONDUCTION/VALENCE Band Satisfying – REDOX (Reduction & Oxidation) CB/VB – More -ve/+ve – H_2O Redox Potential ENERGY BG ≥ 1.23 eV – H_2O Split - H_2 and O_2

hotoCATALytic Water-SPLIT

hν Chemical Energy
H_2O $H_2 + 1/2\ O_2$
Efficiency – Semiconductor Band Structure Efficient H_2 production - Visible-light-driven Semiconductors - Bandgap - 1.23–3.0 eV

Two-Dimensional Nanomaterials

- Since Discovery of Graphene from Graphite Exploration of 2D-NMs Intensified
- Planar (Graphene), Quasi-planar Other NSs Form Family of Designer's Nanomaterials Programmable Structure/Energy Band Gaps

G-C3N4-HETEROSTRUCTURE – PROBLEMS

- Design of Band Structure Alignment
- Positioning for REDOX Reaction
- Enhancement of Efficiency
- Cost Effective Precursors

Design of Heterostructures

- Cu_2O/g-C_3N_4 ,
- Graphene / g-C_3N_4 ,
- CdS / gC_3N_4 ,
- TiO_2 / g-C_3N_4.
- Untreated g-C_3N_4 / Sulfidized g-C_3N_4

Challenges

- Durability/Stability & Efficient Recycling
- Better Precursors – Critical Decision
- Newer Heterojunction & Homojunction – Needed
- Carbonaceous Semiconductors

Metal and Non-metal Doping, Defects, and Interaction Mechanisms of Multiple Functions – Optimal Hydrogen Production and Cost Effective Catalyst

CONCLUSIONS

2D–Semiconductor Nanosheets Appropriate Photocatalyst With Adjustable Parameters
Rugged System Possible Right Kind of Precursor and Processing – Necessary Opportunities – Almost Unlimited

SCOPE AND POTENTIAL OF COALBED METHANE TO HYDROGEN PRODUCTION IN INDIA

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Extended Summary

In India, presently 7 blocks are commercially producing coalbed methane (CBM) (aprox. 3.0 MMSCMD). With the recent completion of the national gas pipeline grid under "Urja Ganga Project" in the eastern part of the country, there is extreme pressure on CBM operators to increase methane production from their respective blocks. The continuous inclination towards the development of clean alternative energies of world countries looking for better use of energy resources. Methanol, ethanol, H_2, fuel cells, etc. are the emerging options for clean energy. Clean hydrogen is hyped as the future fuel, likely to deliver an excess of carbon-neutral energy by 2030. However, hydrogen production from different sources is in the nascent stage in India. The conversion of CBM to hydrogen is a very lucrative, technically, and economically feasible option. Because the average calorific value of CBM is aprox. 8500 kcal/kg and hydrogen is aprox. 30,000/- kcal/kg. The high calorific value of hydrogen and source material for fuel cells offers excellent economics to the operators. In addition, CH_4 to H_2 conversion through CO_2 capture and its injection in reservoirs provides an added opportunity for enhanced coalbed/shale gas recovery. Generally, there are four main sources for the commercial production of hydrogen such as natural gas (48%), oil (30%), coal (18%), and electrolysis (4%). The thermal catalytic conversion of methane to hydrogen is a well-known technology. The cracking of CH_4 through thermal dissociation involves molecular components of CH_4, H_2 and carbon being separated at about 750°C deprived of harmful emissions. About, 95% of the H_2 in the world is produced using the steam methane reforming process. Here, 100% of the carbon in the received CH_4 is eventually converted to CO_2. In order of generating 1 molecule of CO_2, 4 molecules of H_2 are formed, with the steam causative of the extra hydrogen. Hence, about 250,000 scf of CO_2 may be produced per 1 million scf of H_2 production from CH_4 dissociation. Likewise, 1 million scf of H_2 may produce 13 metric tons of CO_2, i.e. 19,253 scf of CO_2 in one metric ton.

The National Hydrogen Mission targets to aid the government in achieving its climate targets and creating India green hydrogen centre, action toward net-zero emissions. The current green hydrogen production costs range between □300 and □350 per kilogram in India. Hydrogen is low-priced and its burning produces only water and produces thrice energy as a comparable amount of petrol. The operators like Larsen & Toubro, Reliance Industries (RIL), NTPC, Indian Oil Corp, BPCL, JSW Steel, Jindal Steel and others, have publicised ambitious plans to install green hydrogen production projects in India. Usually, the produced CBM gas composition contains >97% CH_4, about 2% C_2H_6 and 1-2% water. The mass ratio of carbon to H_2 in CH_4 is 3:1. In terms of mass, CH_4 is (4.032/16.04) x 100 = 25.13% H_2 and (12.01/16.04) x 100 = 74.87% carbon. Therefore, CBM thermal dissociation through the steam reforming process is a good option for obtaining hydrogen. Also, the estimates of hydrogen production from CBM gas appear to be an excellent alternative and have a great scope of development in India. Hence, it is proposed to have a pilot-scale demonstration plant for methane to hydrogen conversion at the CBM production block for confidence building and subsequently large scale commercial implementation.

Keywords: Coalbed methane, Hydrogen production, Potential and Scope, Technological options, Pilot-scale demonstration.

Dr. V. A. Mendhe was born on 16th May, 1973 in Madhya Pradesh state of India. He has obtained Ph.D. in Applied Geology – on the topic "Geologic and petrographic controls on coalbed methane from the coal seams of the northern part of Cambay basin, Gujarat from the Indian School of Mines, Dhanbad in 2008. He has 26 years of experience as a Research Scientist/Field Geologist in applied and basics of coalbed methane, shale gas, coal geology and organic petrology. Dr. Mendhe has done extensive studies on Indian coal, lignite and shale deposits for reservoir characterization, gasification and other utilities. Dr. Mendhe has vast experience in coal and shale exploration, mining geology, gas potentialities, maturity analysis, sorption studies, reserve estimation, porosity and permeability-flow mechanism, production development technologies, reservoir simulation and modelling, GHG emission inventories from Indian coal mining and oil and gas system, coal mine methane potentialities and feasibility, coal mine safety, underground coal gasification, geologic CO_2 sequestration potentiality estimation, sorption induced strain of coal shale and advance recovery of methane, climate change etc.

Dr. Mendhe is the Project Leader of the "National shale gas project" funded by the Ministry of Coal, Govt. of India and "Advance Recovery of CBM and Shale Gas" funded by CSIR, New Delhi. Also, lead of national shale gas mission project and shale gas committee in India. Dr. Mendhe has completed about 155 R&D projects sponsored by Govt., public and private sector companies. He has more than 172 research publications to his credit in the international journal of repute, book chapters, conference proceedings and lecture notes. He has designed and developed various indigenous equipment's used for CBM and shale gas exploration and reservoir characterization studies. Dr. Mendhe is the recipient of Dr. J. Coggin Brown Memorial Gold Medal in Geological Sciences, MGMI for his outstanding contribution in Geological Sciences. He also awarded for best SCI papers with highest impact factor (for year 2016-17, 2017-18, 2018 – 19, 2019-20, 2020-21) by CSIR-CIMFR. Dr. Mendhe is a member of the editorial board of Int. journals and scientific magazines, reviewer of several international journals of repute, member of different technical committees of Govt. of India and scientific project review committees. Dr. Mendhe has guided 18 number of Ph.D, 34 M.Tech and 18 M.Sc.Tech/M.Sc. thesis on coal, shale gas reservoir and other mining geological studies in India. He examined several Ph.D theses from different institutions and was appointed as an examiner for M.Tech and Ph.D viva voce. Dr. Mendhe was on deputation to Bhutan, Thailand, China, Malaysia, Singapore, Indonesia, Turkey, USA, Norway, France, Sweden and Denmark in connection with the research project and speaker in an international forum. Dr. Mendhe is a life and fellow member of several professional national and international societies like the Geological Society of India, Banglore, Indian Science Congress Association (ISCA), Kolkata, Association of Geochemistry, Hyderabad, Jharkhand Geo-Scientist Association (JGSA), Ranchi, The Gondwana Geological Society (GGS), Nagpur, Indian Mining and Engineering Journal Readers Forum (IME), Bhubaneswar, Indian Geological Congress (IGC), Roorkee, Indian Mine Managers Association (IMMA), Dhanbad, Indian Mining, Geological and Metallurgical Institute (MGMI), Kolkata, The Society of Organic Petrology (TSOP) and International Committee of Coal and Organic Petrology (ICCP).

Indian Coal Gasification Strategy: Current Status and Way Forward

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Extended Summary

Presently, the Govt. of India is emphasizing on the coal-based methanol economy, to ring-fence India from the import of crude and petroleum products vis-à-vis to shield the country from the global volatility in the oil and gas market. India has a huge potential in the form of abundant coal reserve to produce alternate products such as methanol, fertilizers, SNG, chemicals, DRI, etc. through gasification route. NITI Aayog has initiated Methanol Economy program that mainly includes adoption of commercially proven suitable gasification technologies for the Indian coal followed by syngas to methanol conversion as well as simultaneous development of indigenous gasification technology integrated with syngas to methanol facility.

For venturing in the area of gasification at commercial level, availability of the suitable gasification technology along with successful operational philosophy is a crucial aspect. As, coal choice may be the least flexible factor due to economic, geographical and political reasons, so, it is necessary to adapt the gasification technology according to the available coal only. Further, identification of matching gasification technology as well as development of operational philosophy, thorough understanding of the physico-chemical characteristics of the coal becomes imperative. CSIR-CIMFR has developed gasifier selection criteria suitable for Indian coal resource and suggested *Matching gasification technology* vis-à-vis *Utilization pattern* & *gasification strategy* for gainful utilization of Indian coal resource.

Methanol Economy Task Forces under the aegis of NITI Aayog has identified two options for gasification program in India for utilization of Indian coal resource towards gasification.

Option-I: Gasification with Commercially Proven Entrained Flow Gasifier (EFG)

Use of low ash containing coal resource available in India, specifically in ECL area has been identified as one of the option. The proposed demo project using low ash coal from ECL area is to be installed at Dankuni Coal Complex (DCC) with membrane wall based high temperature Dry Fed Shell (Air-Products) EFG Technology. Further, high ash coal resource

from neighboring subsidiaries like CCL and MCL can be tested in the EFG at Dankuni Project for gasification performance and to evaluate ash content handling capability specifically with Indian high ash coal resource.

Option-II: Development of Indigenous Pressurized Fluidized Bed Gasifier (PFBG)

CSIR-CIMFR has developed and installed oxy-blown PFBG Pilot Plant and established gasification of high ash Indian coal. The pilot scale developments will provide engineering data to the Engineering Houses for its up-scaling to develop Indigenous Demo Plant. In view of the pros and cons of the installation options, indigenously developed demo scale gasification facility can be installed as a stand-alone facility or can be installed at existing/planned projects. Further, performance of the indigenously developed gasifier can be compared with commercially proven technologies identified under Option-I specifically Shell EFG in view of gasification efficiency, operational performance and finally to evaluate their suitability towards Indian coal resource.

Thus, both the routes, dry feed membrane walled entrained flow gasifier based commercially proven technology adoption and Indigenous demo scale fluidized bed gasification technology development need to be executed in parallel. *Further, for fast and successful development of demo units, programs need to be executed with joint venture between R&D institutions; Engineering Houses and Industries instead of independent parallel programs, as all individual stakeholders have specific strengths at different levels of technology development and implementation.*

HYDROGEN AS ENERGY SOURCE OF THE FUTURE

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Extended Summary

Our world is going through a major transition period in energy sourcing. Consequently, energy driven geopolitics is also changing. Carbon dioxide concentration in air has increased from 280 ppm to around 420 ppm. Average global temperatures are higher than 1 degree above the pre industrial level and all trends indicate that unless we achieve negative emission of carbon dioxide in the near future it is unlikely, that we will be able to maintain average global temperatures within 1.5 degree of the pre-industry level. This calls for a major shift in the type of energy we are accustomed to. We will have to give up fossil fuel and seek renewable sources like solar, wind and hydrogen as our sources of energy besides nuclear and hydropower.

Electric battery vehicles driven by renewable energy have proved to be more energy efficient and are cheaper as compared to hydrogen fuel cell (FCV). With batteries developed to power e-cars, only eight percent of the energy is lost before the electricity is stored in the vehicle's batteries. When the electrical energy is converted to drive the electric motor, another 18 percent is lost. Depending on the model, the battery-powered e-car thus achieves an efficiency of between 70 to 80 percent."

The hydrogen fuel cell requires 2-3 times more energy to drive the same distance as a battery powered vehicle, as the overall Well-to-Wheel efficiency is from 25-35%. However, renewable driven batteries cannot be used for transportation of heavy vehicles. They will need continuous charging and longer charging time as compared to hydrogen fuel cells which are simply replaced at the charging stations.

Hydrogen can be produced either from fossil fuels, which leaves carbon footprints or through electrolysis of water using renewables generated electricity and has therefore zero carbon footprint. Present day research is on producing hydrogen through photo catalytical water splitting, also called artificial photo synthesis.

Hydrogen has colours assigned based on the means of production

Colour labels given to Hydrogen

- Grey hydrogen is generated from natural gas, or methane, through a process called “steam reforming". The process generates less CO2 than Black or brown hydrogen, which uses black (bituminous) or brown (lignite) coal in the hydrogen-making process.
- Blue hydrogen is generated by steam reforming as in the case of Grey, but CO2 generated is captured and stored underground through carbon capture and storage (CSS).
- Green hydrogen – also referred to as “clean hydrogen” – is produced by using renewable energy sources, such as solar or wind power, to split water into two hydrogen atoms and one oxygen atom through electrolysis and is produced in a climate-neutral manner. However, it should be realized that this process is not yet energy efficient.

Hydrogen driven fuel cells can be used in refineries, steel and fertilizer industries. It can also be used in power sector for power generation, in heating residential and commercial complexes and in transportation of heavy vehicles, trains, in aviation and shipping industry. Hydrogen therefore, is considered as the source of energy of the future. Fuel cells supply hydrogen which when burnt using oxygen from air yields energy for the reaction is exothermic and the only other product is water with no carbon emission. Research and development in operating cost reduction and increasing energy efficiency is required before the prevalent costs and efficiency using fossil fuels can be matched. Similarly cheaper and more efficient methods of electrolysis have to be developed before green hydrogen can match the costs of generating blue and then grey hydrogen.

Conventional methods of storing hydrogen in gaseous state at high pressure or in liquid state at cryogenic temperatures and high pressure are cost exorbitant. Losses from the inevitable boiling-off of liquid is an area of concern. While the energy per unit mass of hydrogen is substantially greater than most other fuels, its energy by volume is much less than liquid fuels like gasoline. A fuel cell electric vehicle, will need about 5 kg of hydrogen for a 300-mile driving range. At 700 bar (~10,000 psi), 5 kg of hydrogen will occupy a volume of about 200 liters which is 3-4 times the volume of gasoline tanks typically found in cars. A key challenge, therefore, is to store sufficient quantities of hydrogen onboard, without sacrificing passenger and cargo space. In order to circumvent high volume or high pressure and low temperature, storing hydrogen in solid state through chemisorption or physio adsorption at relatively normal pressure and temperature is drawing attention and is under active research.

Chemisorption:

Chemisorption is a name given to chemical reaction between the surface and adsorbate (often in the presence of a catalyst). Atomic hydrogen binds with other elements to form compounds or solid solutions.

Two types of metal hydrides are already in use

Intermetallic (or interstitial) hydrides where hydrogen occupies interstitial spaces within metal alloys (e.g., $LaNi_5H_6$)

Complex hydrides where hydrogen covalently bonds to a metal to form multi-element anion that combines with other metal(s) through ionic interactions (e.g., $Na(AlH_4)$)

Hydrogen is released from chemical hydrogen storage materials through non-equilibrium processes depleting the adsorbate. The depleted materials have to be removed and chemically processed to regenerate the original hydrogen containing material.

Physio-adsorption

Molecular hydrogen can adsorb onto the surface of porous solids, providing the potential for higher storage densities at significantly lower pressures in physio adsorption. Hydrogen sorbents are high-surface area, micro-porous solids (e.g., activated carbons or metal-organic frameworks (MOFs)) where the diatomic hydrogen molecule adsorbs onto the surface through Van der Waals interactions. MOF s are porous crystals made of metal ions, where large pores within crystal can store hydrogen gas. MOF s have high surface areas and hydrogen adsorption capacities where hydrogen molecules cling to the surface of MOF's cavities and they have a simpler charge/discharge mechanism. MOFs can also store liquid hydrogen and are cost competitive. However, MOFs are still in R and D phase mainly being researched at Berkley

The challenge for all hydrogen storage material development efforts is to develop cost effective materials with high hydrogen density by volume and mass, capable of fast charge/discharge rates within the temperature and pressure ranges of fuel cell operation and able to undergo sufficient charge/ discharge cycles to last the lifetime of the FCEV (Hydrogen Fuel Cell Electric Vehicle).

Another area of contemporary research is in Mg hydrides. In this method hydrogen can be released using light. A breakthrough in hydrogen storage methods is awaited so carbon footprints can be diminished.

A recent report by IRENA (International renewable energy agency) says that by 2050 China could deliver green hydrogen at just over $0.65 per kg by 2050. China is endowed with rare earth metals and is emerging as the front runner in this race. Geopolitics will accordingly swing away from fossil fuel rich states. Apart from restricting the devastations from Climate change, thrust in new source of energy is likely to create millions of new jobs globally, and younger population needs to be skilled accordingly.

HYDROGEN ENERGY A FREEDOM FUEL FOR INDIA: EMPHASIS ON HYDROGEN STORAGE TECHNOLOGY AND APPLICATIONS

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Extended Summary

Energy is directly related to the currency of any nation. No, doubt, it is always in huge demand, but unfortunately always in short supply and insufficient to match the unparalleled population explosion and our changing life style. Undeniably, we are facing an energy crises and it has become the most important commodity and deciding factor not only for national but also for international policies and politics. India ranks fifth in the world in terms of energy consumption. Commercial energy consumption in India was 3.5% of the world consumption in 2002 (as per planning commission reports). Average annual growth rate of energy consumption was about 6% during 1981-2002. Commercial energy demand will grow at 4.5% per annum till 2020, as economy grows at 7 to 8% annually during this period. Exponentially growing gap between demand and supply of commercial energy reveals that there is increased dependence on importing oil from oil rich countries. Oil imports are expected to rise from present 70 percent to as high as100 percent in next two decades. India has only 0.9% of world oil reserves (as against 5% for China; 15% for the USA and 59% for the Middle East). India will always be fuel ravenous if it depends on oil alone. India is currently importing about 130 MT of oil. Because of a continuing rise in the international price, we have to shell out a huge amount in foreign exchange to OPEC (Oil Producing & Exporting Countries) countries. Though the oil price may increase merely by one dollar in the international market, it leads to an additional burden of Rupees 3000crores on Indian economy. During the years 2005 to 2007, when oil prices had skyrocketed from $32 to $65–70, India had to spend additional sum worth about Rupees 1,140,000 crores. This is a vast burden on our economy and substitution of imported oil may lead to the main driver for energy security. Sustainable Energy Pathway for India: Components are; clean coal technologies centralized production of electricity based on increasing share of hydro, nuclear and renewable energies. Decentralized powers through renewable energy are sun,

wind, biomass and small hydro power energies. Alternative fuels for surface transportation bio-fuels electric vehicles, hydrogen and fuel cells vehicles.

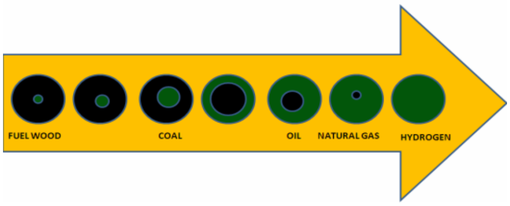

Figure 1. shows the fuel transition based on elimination of carbon content from pre industrial to present times.

The depleting and polluting fossil fuel makes it imperative to find renewable and clean fuel. In the search for alternative fuels, decades of dedicated R&D efforts have revealed that "**Hydrogen''** is indeed such a fuel. Hydrogen is an ideal candidate as a clean energy carrier for both transportation and stationary applications. It is a promising medium for both energy transmission and storage. It is non-polluting, the major by-product of combustion being H_2O and it can be generated through readily available water and a variety of sources, e.g. solar energy (photovoltaic, photoelectrochemical and photocatalytic routes nuclear energy, conventional grid and hydro electricity. Hydrogen has the highest energy density per unit weight of any chemical fuel and has a diversified number of uses, ranging from fuel for internal combustion engines to produce motive power and for generation of electricity and also for motor driven transport through fuel cells. The striking properties of hydrogen and its comparison with other fuels listed below:

Properties	**Units**	**H_2**	**CH_4**	**Gasoline**
Lower heating value	kWh/kg	33.33	13.9	12.4
Self ignition temperature	ºC	585	540	228-501
Flame temperature	ºC	2045	1875	2200
Min ignition energy	mWs	0.02	0.29	0.24
Ignition limits in air	Vol%	4-75	5.3-15	1-7.6

Flame propagation(air)	m/s	2.65	0.4	0.4
Explosion energy	Kg TNT/m^3	2.02	7.03	44.22
Diffusion coeff in air	Cm^2/s	0.61	0.16	0.05
Chemical energy	kWh/kg	39.4	13.1	13.1

Table 1: The striking properties of hydrogen.

One of the key issues surrounding the exploitation of hydrogen as a fuel, however, is the difficulty in storing it efficiently, economically and its transportably. Regardless of the technique employed for hydrogen production, an inescapable aspect associated with the use of hydrogen as an energy vector is its "**storage**". Unlike fossil fuels such as coal or petroleum which are self storable, hydrogen will have to be effectively stored before its deployment in energy systems. It is not difficult to perceive the reason for this. Hydrogen produced under ambient conditions is a gas, in fact, the lightest gas and as such it would immediately escape upward in atmosphere. Its use at an appropriate site requires "**storage**" which is a crucial aspect of the total "**Hydrogen Energy**" concept. But the mode of its viable storage for common uses requires intensive R&D. Both high pressure gaseous (bulky and risky mode) and liquid (expensive cryogenics, thermal and ortho-para conversion losses) forms are rather impractical modes of storage. Chemical storage of hydrogen in the form of metal hydrides represents an attractive alternative, which are the subject matter of intensive R&D efforts being carried worldwide. The advantages of storing hydrogen in the form of metal hydrides include high volume efficiencies, relative ease of recovery, indefinite storage capabilities without loss of hydrogen and a high degree of safety and portability. However, the stored weight of hydrogen per unit weight of solid metal hydride i.e. the gravimetric hydrogen density is rather low and efforts to increase this capacity froms the challenges of current research. A lot of new light weight materials are projected till date such as Carbon nano tubes/fibers, $NaAlH_4$, $Na_XLi_{1-X}H_4$ $NaBH_4$ and many more but none could qualify the required storage capacity target set by DOE department of enegy, USA in year 2010. (10wt% **Volumetric efficiency** and 45 kg/m^3 **gravimatric efficiency)**. Some of these projected materials displayed good Volumetric efficiency but have poor gravimetric efficiency. Similarly a number of them have high gravimetric efficiency but the have low Volumetric efficiency, thus none could qualify to possess the acceptable levels of Volumetric efficiency as well as gravimetric efficiency and are found to be unsuitable as storage material. In india too considerable progress has been made in the field of harnessing hydrogen as fuel. India's hydrogen energy programme is part of the Ministry of Non-conventional renewable energy sources (MNRE) calls its New Technologies. The strategy has been to help these laboratories to acquire expertise in production, storage, and utilization of hydrogen as an alternative fuel. There are a number of major hydrogen energy programmes running in India by various institutes. Some of the major programmes are listed in Figure 2.

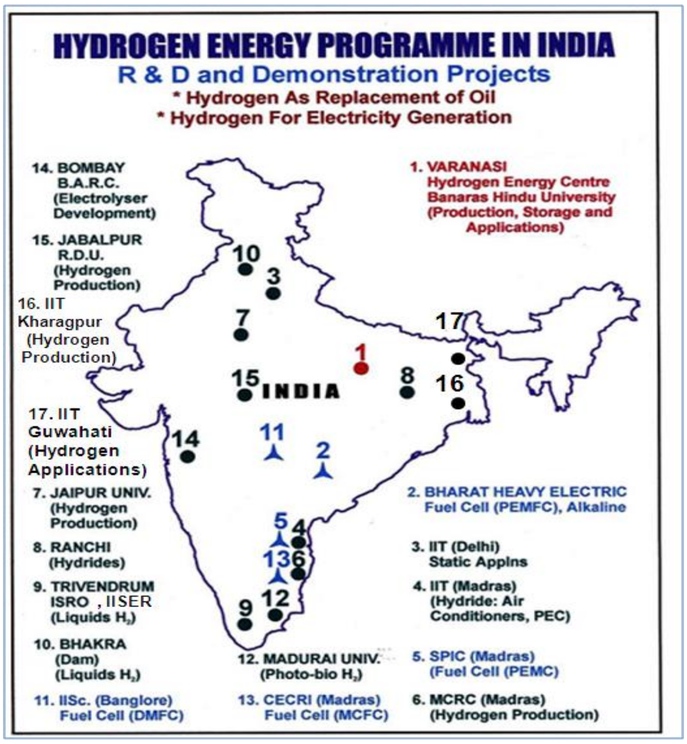

Figure 2. *The major hydrogen energy R&D activities in India.*

To establish hydrogen as fuel in India, a lot of research is required yet to be carried out for knowledge generation about the fuel and its commercial impact on replacement of existing technologies. Special efforts have to put forth to work out the new storage materials which should be reversible, economic and easy to produce in large scale. I hope that the day is not for away when we see hydrogen vehicle and all other fuel based appliances will run on hydrogen and we will feel proud to use such freedom fuel.

WASTE TO HYDROGEN

Shri Rajan Varshney

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Extended Summary

In this paper, a techno-economic study for Hydrogen production from waste and corresponding benefits to economy and sustainability have been studied and analysed. Electricity constitutes only 18% part of India's total energy consumption which can be decarbonized using RE. Balance 82% also needs to be decarbonized to meet the COP 26 commitments. This 82% includes hard to abate sectors like Oil Refining, steel, Cement, Fertiliser, Transport etc some of which can't be fully decarbonized only by targeting electricity. Hydrogen is pivotal to any decarbonisation strategy being highly versatile additionally acting as an energy carrier linking various sectors.

India's Installed capacity at about 400 GW includes 150 GW RE including large hydro. Maximum peak load is about 200GW and baseload is much less. The COP 26 target of 500 GW RE entails substantial difficulties in Grid stability and is highly intermittent in nature. It requires energy storage to meet demand supply mismatch and make RE Dispatchable Round the clock.

Hydrogen can provide required storage and also can supply base load Power through Fuel cell reducing dependency on Fossil fuels. Hydrogen Storage Systems can provide large scale and even very long duration energy storage of the order of 1 GWh to 1 TWh. Converting excess power to Hydrogen and using as and when required for various desired applications at convenient locations unfolds a strategic shift in terms of renewable integration, involving flexibility as well as sustainability.

Hydrogen can be made from various feedstocks. When it is made from Fossil fuels like Coal, Natural Gas etc using SMR(Steam Methane Reforming) or Gasification without carbon Capture, it is called Grey or Brown Hydrogen and emits lot of CO2. Green Hydrogen can be produced from renewable feedstocks like water, Organic Waste, Sewage sludge etc. using RE through various methods like Thermochemical Processes, Electrolysis, Gasification of waste, Direct Solar Water Splitting Processes, etc. Green Hydrogen has nearly nil Carbon

emission. Hydrogen can also be produced from abandoned Gas fields and can also harnessed as free Hydrogen Molecule, all being nearly nil Carbon.

Out of various hydrogen production routes, analysis indicates hydrogen from biomass/waste can be produced at least cost but also can reduce air , water and soil contamination. Further, green Hydrogen can facilitate faster and sustainable energy transition cutting energy imports even energy export. Moreover waste is available everywhere and needs to be tackled in a sustainable manner to avoid soil,water ,air pollution and also avoiding release of Methane can help in combatting climate change".

Further decentralised production of waste near point of use can cut the cost of storage and transport substantially.

Decentralised Green Hydrogen production at optimum price can boost proliferation of microgrids for electricity, heating, cooling and transport in a big manner.

Green Hydrogen can make India self-reliant and facilitate its journey towards carbon neutrality by 2070. Hydrogen from waste promises beneficence for PPP - viz People, Planet and Profits and putting India on a high growth trajectory.

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