

Process Intensification for the Production of Green Hydrogen as Sustainable Model

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Abstract:

With the Increase in the Daily Needs of the Living Beings, the Need of Energy has also raised as well. Thus making Energy an Essential Part of the Life of All Living Beings. The Source which Man has been using ever since the beginning of Industrial Revolution is Non-Renewable Sources of Energy such as Crude Oil, Coal, Coke, Petrol, Diesel etc. These Non-Renewable Sources of Energy has to a lot of environmental problems with the release of Carbon Monoxide, Carbon Dioxide and Other Green House Gases.

During the Consumption of these Fuels in various industrial processes, Green House Gases are produced and Released in the open environment. These causes Environment Pollution, Air Pollution, Soil Pollution and Water Pollution leading to various Diseases to All Living Beings in the Eco-System.

As Solution this to these Problems, the Idea of Creating a Energy Source which Environmental Friendly and Sustainable in Nature should be used. The Source of Energy which were later found are known as Renewable Energy Sources. Eg. Solar Energy, Wind Energy, Tidal Energy, Hydropower Energy etc.

Green Hydrogen is also Green Source of Energy which is Presently being Explored as it can be said the Best Environmental Friendly Energy Source. This Study Focuses on the Various Hydrogen Production Technologies and the Modern Forthcoming Technologies for the Efficient Production of Hydrogen in A Green way on A Bulk Scale.

Keywords: Hydrogen Fuel, Green Fuel, Electrolysis, Sustainable Fuel, Renewable Energy, Green Hydrogen, Electrolysis, Process Intensification of Green Hydrogen

1. Introduction:-

The Evolution of Mankind has it's own challenges but we have successfully overcome all of the with New-New Technological Advancements. The Technological Advancement made Men's Life Easy. Instead of making things by hands, Man used machines to make things for his comfort. This Comfort which Man received from Machines had a Very High which the Environment Paid.

The energy which Industrial Revolution Required was Coal and Petroleum Products. Their Consistent use caused Water Pollution, Air Pollution and Soil Pollution.

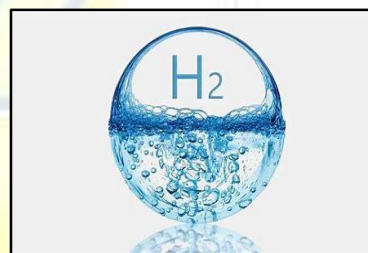
These Pollution made it important to Find a Energy Source which is Sustainable and minimizes or doesn't causes Pollution. This Journey lead to the Foundation of New Technologies such as Windmills, Hydroelectric Power Plant, Tidal Turbine, Tidal Barrage and Solar Power Cells for the Solar Panel etc.

Even though these Technologies are Renewable, their manufacturing requires various metals and alloys to be formed. This Process creates Pollution as well. To Avoid, such formation of Pollution, we Prefer Hydrogen as Sustainable Energy Source.

1.1 What Is Hydrogen?

Hydrogen is gas which is widely available on the Planet and mass of the universe consist of 75% of Hydrogen. Hydrogen is the Most Abundant Chemical Substance in the Universe, Constituting Roughly 75% of all Normal Matter. At Standard conditions Hydrogen is a Gas of Di-Atomic Molecules having the Formula H₂. Hydrogen is a Gas which is Colorless, Odorless, Tasteless, Non-Toxic and Highly Combustible. On Earth, Vast Number of Hydrogen Atoms are contained in Living Beings as Plants, Animals, Humans as well as Water^(1,4,5).

Hydrogen can be said as Sustainable and Eco-Friendly Fuel as Hydrogen Produces Water. Like Fossil Fuels, produces Greenhouse Gases; Hydrogen Produces Water in the Fuel Cell. To Produce Hydrogen, we can use Any Form of Energy such as Solar Power, Nuclear Energy, Wind Energy, Hydropower, Biomass and Natural Gas etc^(1,4,9).



1.2 Why Is Hydrogen Important As A Future Clean Energy Source?

Presently, Energy the which we use is the form Natural Gas and Petroleum. But, their Consumption leads to the Formation of Greenhouse Gases. The formation of these Gases, is Harmful for the Environment. They cause Global Warming in the Planet. We Prefer them, cause they are Comparatively Cost Efficient than Eco-Friendly Equipment which are Powered by Electricity or BioFuels^(1,9,5).

The Presently Vehicles which uses Petroleum Fuels which Produces Carbon Monoxide and Carbon Dioxide. To Minimize their Formation, Hydrogen can be used in Vehicles.^(9,4,18)

Hydrogen could be soon used in Vehicles. The Fuel Cell uses Hydrogen as Reactants and Produces Water. Such Vehicles are Future Technology is Essential for the Modern World's needs.

2. Classification Of Hydrogen Production Process: -

There are Various Production Process for Producing Hydrogen and their Production Process are Classified on the bases of Colour Spectrum. They Classified as Below:-

2.1 Blue Hydrogen:-

For the Production of Blue Hydrogen, we using Fossil Fuel or Natural Gas as reactant. The reaction, Produces steam which is later used to Produce Hydrogen but with Carbon formed during the reaction is Captured, Stored and used for Other Processes. This Process of Producing Hydrogen from Steam is known as Steam Reforming.

Steam Reforming is also known as “Low Carbon Hydrogen Process” as Carbon is Produced as a By Product but Later this Newly Formed Hydrogen is Captured. After that, it is used in the Refrigeration, Cooling and Fire Extinguisher Industry. ^{15,16}

2.2 Grey Hydrogen:-

Grey Hydrogen is used widely for the Production of Hydrogen. In production of Grey Hydrogen, natural gas or methane is used and the process is known as Steam Methane Reformation. But this Process is not Favored Majorly due to the Production of Greenhouse Gases as by Products. The

constant use of Grey Hydrogen leads to emission of Carbon Dioxide Emission and it causes problem to the mission of net-zero carbon emissions. ^{15,16}

2.3 Black And Brown Hydrogen:-

Black Hydrogen is one of the Harmful Hydrogen Production Process, here Black Coal or Brown Coal (Lignite) are used. When Hydrogen is Produced in this Process, Green House Gases are Formed cause of the Breakdown of carbonaceous or organic materials. During the Gasification of Black Coal or Brown Coal (Lignite), oxygen is heated at a high temperature which is more than 600°C. This would lead to the formation of Hydrogen with Carbon Dioxide when water reacts with Carbon Monoxide.

This Process can't be Recommended as it Produces Green House Gases. ^{15,16,19}

2.4 Pink Hydrogen:-

In Production of Pink Hydrogen, Water is first Electrolysis where the Source of Energy is Nuclear Energy. The which is used in this Process is the Waste Energy from the Nuclear Reactors which are in the form Heat. Pink Hydrogen is the One of the Most Efficient Processes in Production of Hydrogen and the Cost of Production is Low than Others. ^{16}

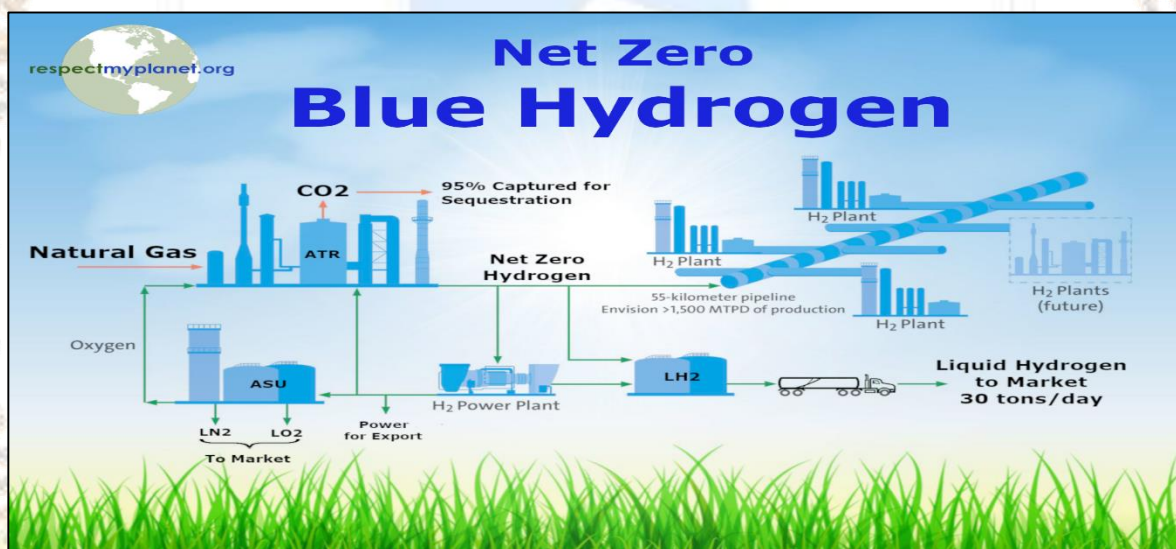


Figure 1

2.5 Turquoise Hydrogen:-

Turquoise Hydrogen is a New Hydrogen Production Process. Therefore mostly it is used in Laboratory Level Only. The Production Process of Turquoise Hydrogen is Known as Methane Pyrolysis. As the Name Suggest; in this Process Methane is Produced as a By Product with Hydrogen as a Primary Product. The Methane is formed from Natural Solid Carbon.

It is also a type of “Low Carbon Hydrogen Process” or “Low Emission Hydrogen Process” due to Production of Methane in the Process. Pyrolysis is Preferred Process to avoid the generation of Carbon Dioxide but Methane is formed from Solid Carbon instead. ^{15,16,23}

2.6 Yellow Hydrogen:-

Yellow Hydrogen is a New Term which Refers to Production of Hydrogen from Electrolysis but it is powered by Solar Energy. Yet, the Process can refer to Electrolysis Powered by Electricity from Any Type of Resource whether it be Renewable or Non-Renewable. Yellow hydrogen could be said as the cleanest man-made gas when produced with

Electrolysers. But Still the Cost of Production is way higher than the Cost of Grey Hydrogen. ^{16, 24}

2.7 White Hydrogen:-

White Hydrogen can be said as naturally-occurring geological gas. It is occurred through fracking in the underground deposit. Presently there is No Process to Extract White Hydrogen from Underground Deposits. Still, it's Assumed that the Extraction Efficiency is Not gonna that Very High. ^{16, 25}

2.8 Gold Hydrogen:-

Gold Hydrogen is a New Hydrogen Production Technology. This technology uses depleted oil reservoirs which are goanna be abandon soon. The Resultant Hydrogen produced is carbon free. This process revies the life of these abandoned wells. Gold Hydrogen is produced biologically and in the subsurface. ^{17}

2.9 Golden Hydrogen:-

Golden Hydrogen is also a recently developed process for the production of hydrogen. In this process, Hydrogen is produced in a Solar Hydrogen Generator using the Solar Energy. Solar

Illumination is carried out in Solar Hydrogen Generator where All Chemical and Physical Process reacts with reactant; Water for the Production of Hydrogen. ⁽⁸⁾

This intimate integration of functions is typically at submeter scale and often at centimeter down to nanometer scale. Golden hydrogen is produced by dedicated solar hydrogen generators, defined as devices integrating all physical and chemical processes needed to directly produce hydrogen from water by solar illumination. This intimate integration of functions is typically at the sub-meter scale. ⁽⁸⁾

2.10 Green Hydrogen:-

Green Hydrogen is form of Hydrogen which is produced from the Electrolysis Process. The Energy for Electrolysis Process is based on Renewable Energy Sources. The Major Form of Energy is from Renewable Energy Sources such as Solar Energy, Wind Energy and HydroPower. Afterwards, this Produced Energy is used for the Electrolysis the Water Present in the Electrolysers. The Electrochemical Reaction takes Place inside the Electrolyzer, where Hydrogen and Oxygen is Produced from Water. This Process is considered to Superior Process as the Compared to Other Processes, in this Process; Hydrogen is Not Produced along with Carbon in any form. This Process is Very Expensive and Less Efficient compared to Others as well the Round Trip Efficiency of the Process is around 40%-50% . ^(3,5,9,13, 16)

3. Why Green Hydrogen Should Be Choose Over The Conventional Fuels? and Advantages Using Of Green Hydrogen Fuel.

The Present Environment of Planet is Largely Affected by Presence and Emission of More Carbon in it. It Exist cause of the Consistent Use of Conventional Fuels. The Conventional Fuels will always cause Carbon Emission in one or the Other Form. We must Forbid their Use Soon for the Sake of Our Environment.

To Save the Environment, there are Various Treaties which are Created with the Objectives to Minimize Pollution and Encourage the Use of Green Products and Technologies such as

1. The Geneva Convention on Long-Range trans-boundary Air Pollution, 1979.
2. Convention for the Protection of the Ozone Layer, 1985 (Vienna Convention).
3. United Nation Framework Convention on Climate Change, 1992.

Green Hydrogen has the Ability to Revolutionize the World. The Green Hydrogen Fuel would be Soon Replacing the Traditional Fuels in Industries such as Steel, Refineries and Chemical Industry. Presently, these industries require Petroleum based Energy to kickstart but in the Future with Green Hydrogen will be used instead of Petroleum and the Product produced will be Water instead of Carbon. ^(16, 12)

4. Future Hydrogen Production Technologies:-

There are New Technologies which has changed the Direction of Hydrogen Production. These Technologies are currently Under Development and has the Potential to

Improve the Efficiency of Hydrogen Production. They are as Follows:-

4.1 Methane Pyrolysis:-

Methane Pyrolysis is one exciting new process for producing hydrogen using methane. Here, Natural Gases is Thermal Decomposed and Later; Plasma Decomposed which leads to the formation of Hydrogen and Carbon. But the Carbon formed in this Process is in Solid State, so it Stored to use in Other Processes. The Hydrogen is also Stored Later in Containers for Further Use and Transportation. This process has a requirement of very High Temperature which is Not Very to Maintain.

Commercial Research on Methane Pyrolysis Technologies is going on where majorly it is focused on Reducing the cost of Plasma-Based Technologies. This is the Best Possible Technology with Zero-Green House Gas Emission. Still the on going Challenge is to Find Methods to Optimize the Production of Hydrogen and Solid Carbon. ^(16, 26)



4.2 Solar Hydrogen Production:-

These are Hydrogen Production Process based on Photolytic Research to Separate Oxygen and Hydrogen from Water. These Processes has the Ability to Bring change just now Development is going on to make the Process Efficient. Although, these Technologies are Green Technologies but their Cost is Significantly Very High Now. These New Technologies are;

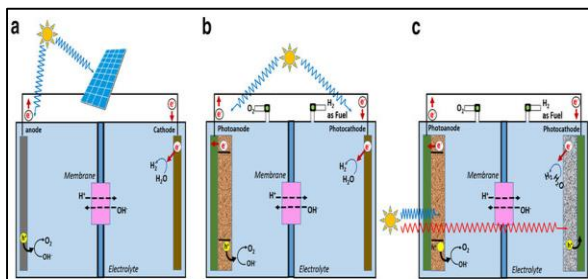
- (i) Photocatalytic Water Splitting,
- (ii) Photoelectrochemical Water Splitting.

These technologies being in their initial stage, are not initially viable yet cost wise. Still, they can be mentioned to be the most efficient process which as also have zero impact harmful impact on the environment. ⁽¹⁶⁾

4.2.1 Photoelectrochemical Water Splitting Process:-

In the Photoelectrochemical Water Splitting Process, where Specialized Semiconductor Material; Photoelectrochemical Material which uses Sunlight to produce Hydrogen and Oxygen by Dissociating Water Molecules.

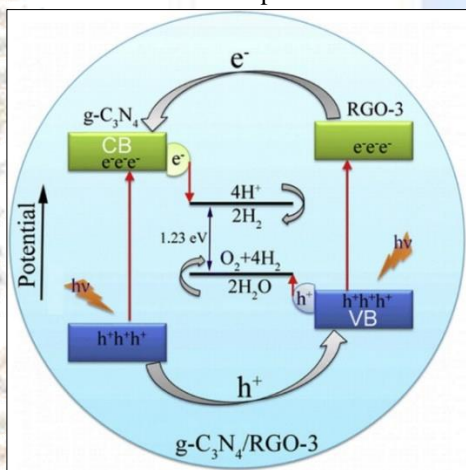
In this Technology, Chemical Energy forms Hydrogen which is Produced from Photoelectrochemical Material's Solar Energy. This Technology can be Stated Similar to Photovoltaic Electricity Generation as the Photoelectrochemical Material is used. The Sunlight play's a Vital Role as it Energies the Water Slitting Process. Photoelectrochemical Reactor can be Constructed in Panel Form for Electrode System and even as Slurry-Based Particle Systems. ^(16, 27)



4.2.2 Photocatalytic Water Splitting:-

In Photocatalytic Water Splitting Process, we use single visible-light-responsive photocatalyst which breaks down water molecules into Oxygen and Hydrogen. The Photocatalyst used in this Process is required to have Sustainable Thermodynamic Potential Splitting the Water. Research is going on to produce a High Performance Photocatalyst. As well, the Photocatalyst should have High Light Absorption Characteristics and High Energy Transfer Rate with Suitable Physical Properties.

Still there is a Requirement for this Process to be Mature. Therefore, there is a Requirement for this process to improve in the part of Efficiency, Durability and Cost for the Process to be used World-Wide. This Process would be Successful when the Photocatalyst is Perfect which is Efficient, Effective, Durable and High Electron Transfer Catalyst. The Materials required for this Reactor should be Multifunctional and economical price. {16, 28,29}



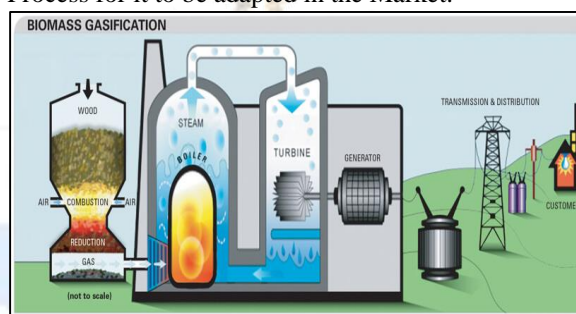
4.3 Biological Hydrogen Production:-

In Biological Hydrogen Process, Hydrogen is produced directly from Natural Resources along with Organic Matter. It is also known as Photobiological hydrogen production process. In this Process, natural metabolic reaction takes place with the help of Microbes to produce Hydrogen and Oxygen when Water is Consumed. Organic Matter will be Specialized Microorganisms, such as green algae and cyanobacteria. The estimated production capacity of this Process would be around 1,500 kg/day in the long future. Some photosynthetic microbes use sunlight as the driver to break down organic matter, releasing hydrogen. It can also be known as photo-fermentative hydrogen production. The Major Challenge for this Process is to Improve Efficiency of Hydrogen Production and low solar-to-hydrogen efficiency. {16, 30, 31}

4.4 Biomass Gasification:-

In Biomass Gasification Process, Microorganisms consume Biomass and produce Hydrogen after Digesting Biomass. The Production Process works on the Principle of Fermentation which occurs in Dark Environment. The

organic matter consists majorly; refined sugars and raw biomass sources such as corn stover, and even wastewater. These microbes can break down complex molecules through many different pathways, and the byproducts of some of the pathways can be combined by enzymes to produce hydrogen. Researchers are Planning to make the Production Process Efficient by Enhancing the Design of the Fermentation Chamber to Hydrogen Faster and More in Quantity and therefore the Temperature Requirement is Higher than 700°C. In this Process, Biomass removes Carbon Dioxide from Environment and Grows by consuming Carbon Dioxide. Commonly Organic Material used as a Biomass source consists of forestry crops & residues, agricultural crops and residue, sewage, industrial waste, animal waste, and municipal solid residues. But the Process has Low Efficiency than Required with High Production Cost, therefore it is required to Economize the Process for it to be adapted in the Market. {16, 30}



4.5 Hydrogen production by Rhodospira rubra:-

In this Process, Photosynthetic bacteria such as R. rubra is used in the biological production of hydrogen as these substrate are driven high conversion efficiency and their ability to use several varieties of substrates for the hydrogen production and cell growth. Still this Process is Challenging one as we have to understand and maintain the Norms & Guidelines of the Process while dealing with metabolism, enzymes and the mechanism of hydrogen production to Enhance the Efficiency of the Process. During Photoheterotrophic Metabolism, bacteria use the substrate, light and, enzymes for their development.

In this Production Process Following Requirement are Necessary:-

- (i) A light source;
 - (ii) Anaerobic conditions in the presence of inert gas;
 - (iii) An example electron donor substrate; lactic acid etc.;
 - (iv) A production medium which limited in nitrogen source.
- Studies on this Process is carried out by with using Various light sources, substrates and media. The Substrate is Preferred if it Improve the Production of Hydrogen or other products such as Poly Hydroxy Butyrate. These High-Quality Substrate belongs Category of lactate and malate. The Citric Acid Cycle, the Photosynthetic Membrane and Enzymes play an important role in the mechanism of hydrogen production. {32}

4.6 Lignocellulose derivatives electrocatalytic oxidation coupling HER:-

Lignocellulose are used in this process as it is an abundant resource and has renewability advantages as well. They can be used into fuels and valuable chemicals by converting them through biomass refining technology. In this Technology, lignocellulose or lignocellulosic derived intermediates are used as anodic electrochemical oxidation substrates for replace the sluggish oxidation evolution reaction which would improve the efficiency of Water Electrolysis. This would lead to production of Hydrogen

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