Hydrogen Energy: Production, Storage, Transportation and Safety

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Lecture - 29
Technical Comparison of Various Hydrogen Production Routes

Now, that it has been accepted that the concept of zero emissions or decarbonization is not possible without the use of hydrogen and hydrogen will play a dominating role towards the decarbonization of several important sectors. Hydrogen has the potential to address the energy and environment related challenges; however, this is possible only if the entire value chain of hydrogen is clean and emission free.

We have seen in the earlier classes the different methods of hydrogen production from hydrocarbons. Production of hydrogen from hydrocarbons is cost effective, but not sustainable. For sustainable hydrogen production, it has to be produced from either renewables or from fossil fuels with carbon capture use and sequestration that adds up to the cost.

But in long run with the increased renewables deployment, reduction in the renewables power, cost in economies of scale working out we will have learning by scaling up. And then improvement in the technology, it is expected that the scenario will change in future. Now, in this class we will compare all the hydrogen production methods on technical basis. So, we will see the important advantages, disadvantages what are the efficiency associated with the various hydrogen production methods and the associated economics we will see in the next class.

Now, when we compare all the hydrogen production routes, there should be some parameters on the basis of which we compare those. Like if we compare a technology with another technology, we have to match what is the advancement level, whether this is at a developmental scale or it is at an industrial scale. Whether the infrastructure corresponding to that is available, at what price the feedstock is being purchased.

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Comparison of various Hydrogen Production Routes

Parameters –

- production technology and its advancement level
- infrastructure available
- price of the feedstock

Goal to make the hydrogen production systems:

- efficient
- affordable
- reliable
- safe
- ready for different types of end user needs(small or large scale, stationary or portable etc)
- increase production capacities
- reduce cost

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And then when it comes to the goal to make the hydrogen production system, it definitely should be efficient, affordable, reliable safe and ready for end user application. Whether it is in terms of the scale of production, it is used for small scale or large scale production for stationary or for portable application. Requirement is we have to enhance the production capacities, looking at the growing global demand and also work towards reducing the cost.

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Technologies	Advantages	Disadvantages	Efficiency
SMR	Most viable, mature and widely used method, currently lowest cost, infrastructure exists, can operate continuously year around thus better for providing baseload with high load factors (around 95%), no oxygen requirement, low operating temperature than ATR and POX, high H_2/CO ratio	External heating required, catalyst deactivation problem, high CAPEX and OPEX, high maintenance costs, requirement of low cost and efficient purification technology, crucial is design of the plant and feedstock pretreatment optimization, reliability, cannot be turned on and off readily takes long time, CO_2 emissions so SMR+CCUS	74-85%
POX	Proven technology, reduced requirement of pre-treatment, fuel flexibility, lower content of unreacted hydrocarbons, compact design, easy to start and stop, can upgrade dirtier feedstocks	Low H_2/CO ratio, high operating temperatures, complex handling process due to hydrogen oxidants and very high temperatures, requirement of ASU, in catalytic partial oxidation problem of catalyst deactivation	60-75%
ATR	Lower operating temperature than POX and lower content of unreacted hydrocarbons, more compact than SMR, lower oxygen requirement than POX and lower steam requirement than SMR	Limited commercial units and experience, requirement of oxygen and steam	60-75%
Coal gasification	Syngas produced at lower cost, abundant, cheap feedstock available	Reactor cost high, lower system efficiency, wide variety of feedstock and impurities present, tolerance towards impurities, requirement of low cost and efficient purification system, hydrogen purity obtained, fluctuating yield of hydrogen due to presence of impurities in feedstock, tar formation	35-55%
Methane decomposition or pyrolysis	No emissions, less number of steps involved, value added exotic carbon products, easier separation and purification	Deactivation of catalysts, use of catalyst, use of carbon products as at present demand is not high	

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Now, when we compare the different technologies and see their advantages and disadvantages, the first technology which is most widely used one is the steam methane reforming. This is the most viable and the major technology, which is widely used for hydrogen production, most of the global hydrogen production is by means of this method. Currently it is the lowest cost option and the infrastructure related to hydrogen production using this method exist.

It can operate continuously for year around and thus it is a better method to provide the base load with high load factors, typically around 95 percent. In this method as against the other two methods, partial oxidation and auto thermal reforming, oxygen is not required and compared to those methods it operates at a relatively lower temperature.

We can achieve higher hydrogen to carbon monoxide ratio with steam methane reforming, but the major disadvantage is we require an external heating, we have to burn fuel. So, as to provide the heat of the reaction and catalyst deactivation could be a challenge. So, the design of the reformer plant should be optimized so as to have minimum catalyst deactivation problems.

Having a steam methane reforming plant has a high capital expenditure and operating expenditure, it has a high maintenance cost and the need is after a reforming unit a low cost and an efficient purification technology. So, the crucial for SMR method for hydrogen production is the design of the plant, the feed pre treatment plant design, its optimization, its reliability.

Since it cannot be turned on and off frequently, it is meant for long periods of operation and as such the systems are having heat exchanger. So, these are bulky and carbon dioxide emissions are there. So, an additional requirement of CCUS will be there for sustainable hydrogen production, typical efficiencies from a steam methane reforming plant lies in the range of 74 to 85 percent.

Second method that we have learnt in the course till now, was partial oxidation which is again a proven technology, it has a reduced requirement of pre-treatment. The temperature at which the reaction occurs are substantially high and it has a fuel flexibility. So, in the non catalytic partial oxidation, the requirement of feed pre treatment is not there and since the reaction occurs at a faster kinetics at a higher temperature, the content of unreacted hydrocarbon that comes up in the product gas is relatively lower.

The design of such plants is compact and they are compared to steam methane reforming very easy to start and stop. Any type of dirtier feedstock, the bottom of the barrel refinery fuels which are very difficult to upgrade can be upgraded using partial oxidation. So, there are several benefits of the process, but at the same time there are disadvantages, like the hydrogen to carbon monoxide ratio in the syngas obtained is lower.

The corresponding temperatures at which the system operates is or the operating temperatures are higher. Since, we are dealing with hydrogen as well as oxidants together there is a complex handling process so that it should not go into the flammability or the explosive limits. There is a requirement of air separation unit if oxygen is used as an oxidant and in the catalytic partial oxidation the problem of catalyst deactivation will be there. Typical efficiency for such processes lies in the range of 60 to 75 percent.

The next method is auto thermal reforming which operates at relatively lower operating temperatures than the partial oxidation method and again it has a lower content of unreacted hydrocarbons, which comes in the product gas stream. It is comparatively more compact than the steam methane reforming.

It has lower oxygen requirement than the partial oxidation and lower steam requirement than the steam methane reforming. However, this method has a limited commercial units and a limited experience of using this method for hydrogen production and there is a requirement of both oxygen and steam in the process. Efficiency in the range of 60 to 75 percent.

Coal gasification is another important method for hydrogen production, where the syngas which is produced is obtained at a lower cost, because the feedstock which is used is abundant and comparatively cheaper. Now, the reactor cost is high, that is the disadvantage of this method system efficiencies are lower and based on the wide variety of impurities present in the feedstock, the tolerance towards that impurities is essential to be met.

There is requirement of comparatively lower cost and efficient purification system, because the amount of emissions in the process is higher compared to the earlier three methods. The product purity which is hydrogen we have to obtain, so a purification system is desirable. Based on the impurities present in the feedstock in the coal, the amount of hydrogen that will be obtained, the yield of hydrogen will be fluctuating.

And the major challenge remains is the tar formation in the gasifiers. And typical efficiency for such plants lies in the range of 35 to 55 percent. Now, the means for getting turquoise hydrogen, which has again got interest is methane decomposition or methane pyrolysis. In this method, since the product obtained is hydrogen and solid carbon so as such there are no emissions associated.

The number of steps involved are less and additionally we can get exotic form of carbons, which can be used for various other applications. And since there is a clear cut difference of states of the two products so it is easier to separate and purify the hydrogen gas stream. But associated with the methane decomposition are disadvantages, that the catalyst can easily get deactivated because the product is carbon and that gets deposited onto the catalyst.

Carbon products at present we know that if the hydrogen production takes place through this method, then the amount of solid carbon which will be obtained by methane decomposition that will be higher and at present there is not sufficient demand of that carbon. So, once the demand increases, then this method will also be using the carbon which is being produced revenue can also be generated and it will become more cost effective.

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Biological Routes for Hydrogen Production

Technologies	Advantages	Disadvantages	Efficiency
Biomass Pyrolysis	Syngas produced at lower cost, abundant and cheap feedstock available, carbon neutral	Tar formation, availability of feedstock all the type, variation in hydrogen produced due to impurities present in feedstock	35-50%
Biomass Gasification	Syngas produced at lower cost, abundant and cheap feedstock available, carbon neutral	Reactor cost high, lower system efficiency, wide variety of feedstock and impurities present, tolerance towards impurities, requirement of low cost and efficient purification system, hydrogen purity obtained, fluctuating yield of hydrogen due to presence of impuritiies in feedstock, tar formation, continous availability of feedstock	30-40%
Dark Fermentation	Simple, no requirement of sunlight, CO_2 neutral, can be used for waste recycling	Larger reactor required, need for elimination of fatty acids, low hydrogen yield and rate of production, getting high capacity	60-80%
Photo Fermentation	CO_2 neutral, can be used for waste recycling, can use variety of wastes	Large reactor required, poor efficiency and low rate of hydrogen production, requirement of sunlight, lower yield	0.1 - 10%

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There are few biological route for hydrogen production, like we have seen the bio biomass pyrolysis. Syngas produced using this method of pyrolysis it is at a lower cost and the feedstock we know it is abundantly and available and it is cheap and a process is carbon neutral process. But the major problem associated with this method of hydrogen production is the tar formation in the production plant.

Continuous availability of the feedstock and of same type is a problem. So, the feedstock all variety of feedstock are available and that leads to variation in the hydrogen being produced, because of the presence of different impurities in the feedstock. Typical efficiency from biomass pyrolysis lies in the range of 35 to 50 percent. A similar product method of biomass gasification, wherein the syngas obtained at a lower cost, feedstock is again a biomass which is the process is carbon neutral.

But the major problems associated with this method is the reactor cost is higher, system efficiencies are lower and then we have wide variety of feedstock, continuous availability of the feedstock is the major challenge and then there are impurities present in the feedstock. So, the tolerance is required towards the presence of these impurities.

With hydrogen there are other gases which are in higher quantity. So, a low cost and efficient purification system is desired to obtain high purity hydrogen, because of the fluctuation in the feedstock composition or presence of impurities in the feedstock, the yield of hydrogen is also different, it fluctuates. Tar formation is the major challenge and then continuous availability of the feedstock is also the the problem associated with this particular method.

Efficiency of this process lies in the range of 30 to 40 percent, there are two more biological methods which can be used for hydrogen production dark fermentation and photo fermentation. Although these are simple methods and these are carbon neutral methods, for dark fermentation there is no requirement of sunlight and this can even be used for waste recycling.

But the major challenges associated with this method is the volume of the reactor required is higher. So, large reactor size required, there is a requirement of elimination of fatty acids. The yield obtained and the rate at which hydrogen is being produced is lower and it is important that we upscale it to get high capacity or large amount of hydrogen.

Efficiencies lies in the range of 60 to 80 percent, with photo fermentation again it is a carbon neutral process can be used for waste recycling and variety of wastes can be used for producing hydrogen. The problem remains similar to dark fermentation the reactor size requirement is high, but the process has a poor efficiency and the rate at which hydrogen is being produced is also lower. So, the yield of hydrogen produced is lower and the typical efficiency lies in the range of 0.1 to 10 percent.

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Water Splitting Routes for Hydrogen Production

Technologies	Advantages	Disadvantages	Efficiency
Thermochemical cycles	Waste heat/nuclear/solar thermal to provide the required energy, scalable, can allow large scale hydrogen production, robust, low cost materials requirements, reliable, clean and sustainable method, chemicals are recycled	Corrosion and toxicity of materials, requirement of high temperatures; requirement to design low cost reactors and to design low cost, high volume, flexible system with efficient heat transfer	Nuclear :45%, Solar 17-20%
Electrolysis	Mature technology, no emissions if renewable power used, infrastructure exists, high purity hydrogen and oxygen products	Scaling up, high capital cost, reducing cost, use of less expensive materials, integration, storage and transportation problems, cost effective membranes and catalysts development	60-80%
Photo electrolysis	Clean and sustainable method, abundant feedstock, oxygen and hydrogen products, high purity	Corrosion problems, expensive and toxic materials, high capital costs, low efficiency, lack of materials for efficient conversion, losses in process, better control over process	0.06%
Photolysis	No emissions, abundant feedstock produces both O_2 & H_2, high purity	Low efficiency, lack of materials for efficient splitting	6.00%
Bio Photolysis	Consumption of CO_2, mild operating conditions, pure oxygen and hydrogen produced	Lower yield of hydrogen, larger area reactor required, cost is high, low rate of hydrogen production	10-11%

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We can also get hydrogen, we have seen through various water splitting routes, either thermochemical route or electrolysis or photoelectrochemical or photolysis route. Now, the major problems associated with thermochemical cycles are corrosion and toxicity of the materials. Requirement of high temperatures, requirement of design of low cost reactor as well as low cost materials, high volume is required.

A system which has a efficient heat transfer need to be designed, but there are several advantages also associated with thermochemical cycles. We can use waste heat, nuclear energy or solar thermal to provide the required energy for the reaction to take place. Here the method is scalable and we can use this method for large scale hydrogen production. The materials which are used in the process for the thermochemical cycle these are low-cost materials, process is robust reliable and it is a clean and sustainable method for hydrogen production.

Whatever chemicals we are using the materials we are using that are recycled in the process. When nuclear energy is used for energy input, the typical efficiency of is close to 45 percent, when solar thermal plant is integrated with thermochemical cycle then the efficiency lies in the range of 17 to 20 percent. When the electrical energy input is used for water splitting in the electrolysis, we know that this is a mature technology which has no emissions when renewable power is used to feed to meet the energy requirement for electrolysis.

Already there is infrastructure which is existing and we can get very high purity hydrogen using electrolysis. Oxygen is another product which can be used and can be used for various application, for medicinal applications, it is the cost of the process is the major disadvantage. Reducing the cost is the requirement and that can be done by the use of less expensive materials.

Other challenge, is the integration of these with the different plants like with the solar integration, then storage and transportation could be a problem, use of less expensive membranes, catalyst that development becomes essential for scaling it up for large scale hydrogen production. And efficiency with electrolysis lies in the range of 60 to 80 percent.

In photoelectrolysis, which is again a clean and sustainable method for hydrogen production the feedstock available is in abundance, both sunlight as well as water. And we get oxygen and hydrogen products with high purity. So, both the products can be used for different applications, but the major problems associated with photo electrolysis is the corrosion related problem, use of expensive materials which are toxic.

The high capital cost which is required, the process has a low efficiency and at present the lack of materials which could give efficient conversion, there are several losses in involved in the process. So, a better control over the process is desired. Efficiencies are poor 0.6 percent. We can also use water for photolysis. This is again a clean method of hydrogen production with no emissions, feed stock is abundantly available again we get both the products which are useful and high purity hydrogen.

But the problem is that of efficiency being poor and the materials which are required for this particular method of hydrogen production are not very efficient. So, desirable is to come up with materials which are more efficient towards water splitting, efficiency around 6 percent. Bio photolysis is another route for producing hydrogen from water splitting, which consumes carbon dioxide and it has mild operating conditions producing hydrogen and oxygen.

The challenge associated with the method is lower yield of hydrogen, it requires large area reactor, cost associated is higher and low rate of hydrogen production. Typical efficiencies lie in the range of 10 to 11 percent.

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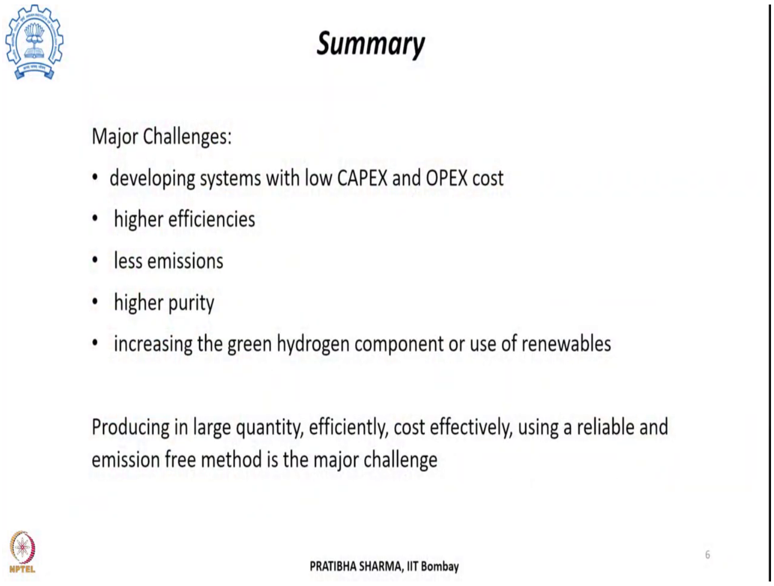

So, to summarize this part, the major challenges associated with the different hydrogen production methods is to develop systems which have a lower capital investment, lower operational cost and maintenance cost, which have higher efficiency less emission. We could get high purity hydrogen and that can all be achieved when we use the green hydrogen component or use the renewables.

And with that we scale up the hydrogen production to get large quantity of hydrogen efficiently in a cost-effective manner using a reliable and emission free method and that is the major challenge in the hydrogen value chain.

Thank you.