GENI Global Energy Network Institute

Hydrogen
for
Large-scale Electricity Generation in USA

September 2011

Deepak Prakash
Research Associate, Global Energy Network Institute (GENI)
deepak.prakash.09@gmail.com

Under the Supervision of and edited by
Peter Meisen
President, Global Energy Network Institute (GENI)
www.geni.org
peter@geni.org (619) 595-0139

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Abstract

In the recent years, there has been a lot of interest in examining clean energy options. It is now recognized that our energy solutions must include a combination of various technologies integrated with energy storage and smart grid approaches. Even now, our energy comes mainly from fossil fuels like coal, oil and natural gas. The electric power sector is still largely dependent on fossil-fuel-based model.

The growing concerns regarding climate change have necessitated implementation of norms for mitigating greenhouse gas emissions. The electric power sector is the most important contributor to emissions. There is urgent need to change the existing system of electricity generation to make use of clean, renewable energy sources. But this change cannot take place all of a sudden. There must be a steady, gradual change of the methods.

Hydrogen derived from renewable sources is a clean energy resource. Burning it produces only water. Using hydrogen as transportation fuel and for distributed power generation in fuel cells is already being studied and in some places implemented. Hydrogen can also be used for utility scale electricity generation in power plants to mitigate emissions. This study is concerned with the feasibility of using hydrogen for large-scale electricity generation in power plants.

A renewable resource assessment in United States is made to know the potential for hydrogen production. Then, various methods of hydrogen production, handling and delivery are studied. The use of hydrogen as a fuel in turbines is also studied along with some strategies that can be employed to make the model realizable in the near future.

Overall, the results of the study give a positive indication that hydrogen can be made use of in the electric power sector. The consequences will be highly beneficial not only to mitigate the emissions problem but also to encourage the utilization of more renewable resources to produce hydrogen.

1. The role of Hydrogen in Electric Power sector

Hydrogen is the simplest and most abundant element in the universe. It makes up about 75% of all matter in the universe. It is a basic element with tremendous potential. It is a non-metallic element with atomic number 1. Hydrogen gas or molecular hydrogen consists of two atoms of hydrogen held together by a covalent bond.

Hydrogen produces clean energy. When oxidized, or combined chemically with oxygen, its only byproducts are heat and pure water. This is why hydrogen bears so much promise as a source of clean energy.

$$H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$$

The energy content of hydrogen is much higher in comparison to other normal fuels like gasolene, coal and natural gas. Specific energy is the energy content of the fuel per unit mass. The specific energy of hydrogen is 141 kilo Joules per gram which is roughly thrice that of gasoline. The below figure gives a comparison of specific energies of different common fuels[1].

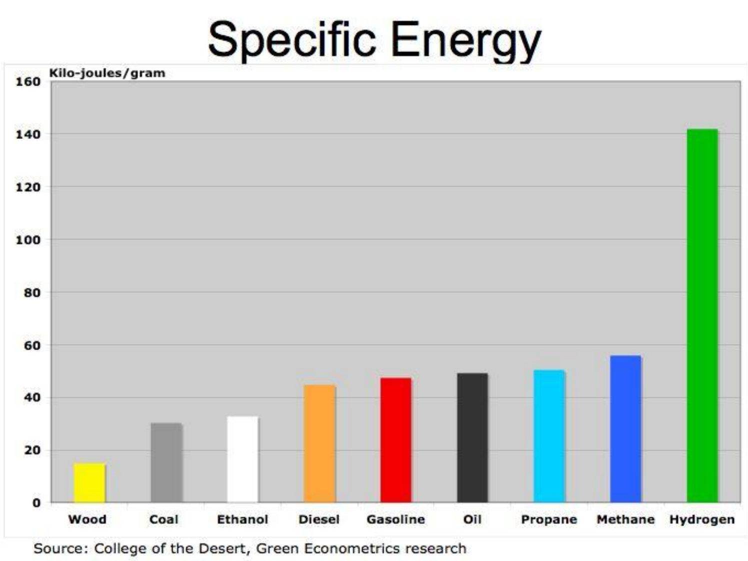

Figure 1: Energies of different common fuels

[1] Source: http://greencon.net/page/3

In the United States of America, electric power sector still largely depends on the fossil fuels. The figure below[2] shows that coal, natural gas and petroleum constitute to about 70 % of the total sources of electricity production as of 2009. The rest of the sources include renewables and nuclear energy.

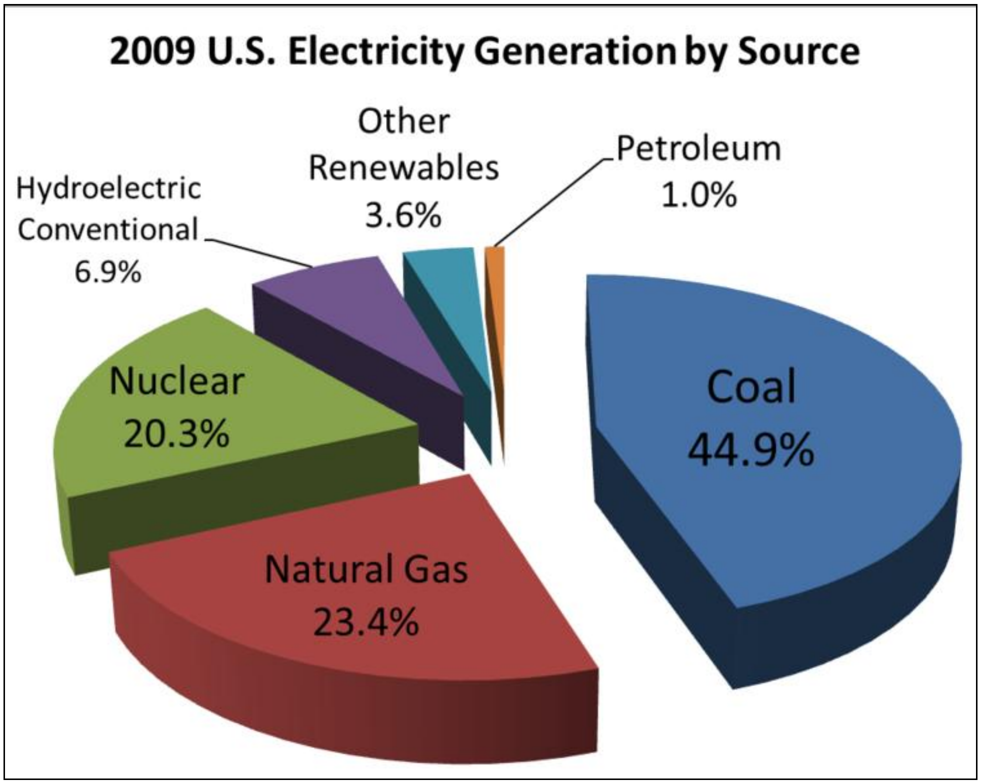

Figure 2: 2009 U.S. Electricity Generation by Source

In 1992, the United States signed and ratified United Nations Framework Convention on Climate Change (UNFCCC). As stated in Article 2 of the UNFCCC, "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

[2] Source: Wikipedia – Electricity generation.

The table below gives the data of US greenhouse gas emissions allocated to different economic sectors. It shows that Electric Power Industry is the major contributor to the emissions over the years. It accounts for about 33% of the total emissions as per 2009 data.[3]

Implied Sectors	1990	2000	2005	2006	2007	2008	2009
Electric Power Industry	1,868.9	2,337.6	2,444.6	2,388.2	2,454.0	2,400.7	2,193.0
Transportation	1,545.2	1,932.3	2,017.4	1,994.4	2,003.8	1,890.7	1,812.4
Industry	1,564.4	1,544.0	1,441.9	1,497.3	1,483.0	1,446.9	1,322.7
Agriculture	429.0	485.1	493.2	516.7	520.7	503.9	490.0
Commercial	395.5	381.4	387.2	375.2	389.6	403.5	409.5
Residential	345.1	386.2	371.0	335.8	358.9	367.1	360.1
U.S. Territories	33.7	46.0	58.2	59.3	53.5	48.4	45.5
Total Emissions	**6,181.8**	**7,112.7**	**7,213.5**	**7,166.9**	**7,263.4**	**7,061.1**	**6,633.2**
Land Use, Land-Use Change, and Forestry (Sinks)	(861.5)	(576.6)	(1,056.5)	(1,064.3)	(1,060.9)	(1,040.5)	(1,015.1)
Net Emissions (Sources and Sinks)	**5,320.3**	**6,536.1**	**6,157.1**	**6,102.6**	**6,202.5**	**6,020.7**	**5,618.2**

Table 1: US Greenhouse Gas Emissions by Sector

The figure below shows the data collected in a graphical form. Electric Power Industry accounts for major portion of the emissions in US.

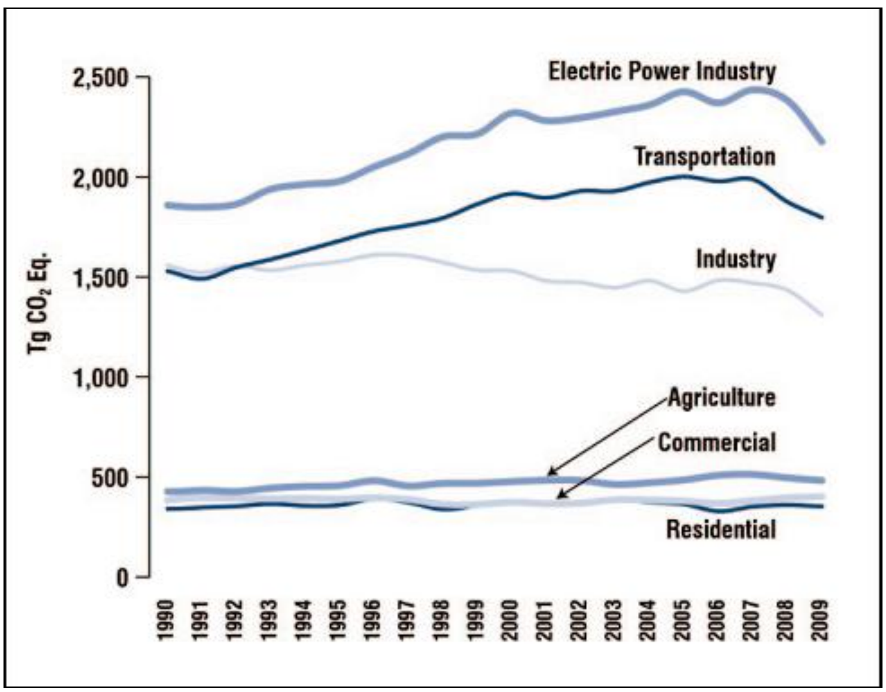

Figure 3: US Greenhouse Gas Emissions by Sector

[3] Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2009 -Executive summary- US EPA

Thus, there is an urgent need for modifying the existing fossil-fuel-based electricity generation methods.

In order to meet the growing demands for electrical energy and at the same time, to mitigate the problems caused by green house gas emissions, we need to look for the right combination of clean energy sources as well as energy storage technologies. Along with the development of renewable energy sources, the existing methods of electricity generation need to be modified. Hydrogen can serve the purpose!

The flexibility of hydrogen allows for its integration in many areas of the system. Hydrogen can act as a clean fuel, which can be combusted in gas turbines to generate electricity. It can also be used as a transportation fuel like gasolene in hydrogen internal combustion engines. It can be used in fuel cell based automobiles to generate electricity electrochemically. It can be used in distributed power generation systems using fuel cells to cater to the electricity need of an office or a small community.

Hydrogen is an energy carrier like electricity. Just like electricity carries energy by transmission lines from power plants to the end users, hydrogen can be employed to carry energy from its source point to the end users by pipelines.

Hydrogen is successfully used as an energy storage medium. The options for electricity storage with the present battery technologies offer many drawbacks. Thus, electricity is used as it is produced. By integrating hydrogen in the system and storing electricity, it is possible to make better use of surplus renewable resources.

The idea is to produce hydrogen from the renewable electricity generated by solar, wind, biomass and other sources. Hydrogen thus produced can be integrated in transportation sector, distributed electricity generation and also utility-scale electricity generation. Thus, hydrogen generated from renewables can be combusted in power plants to produce electricity. This process will not only help in utilizing and developing the renewable technologies, but also will help in mitigating emissions. The figure below shows schematic representation of the model.

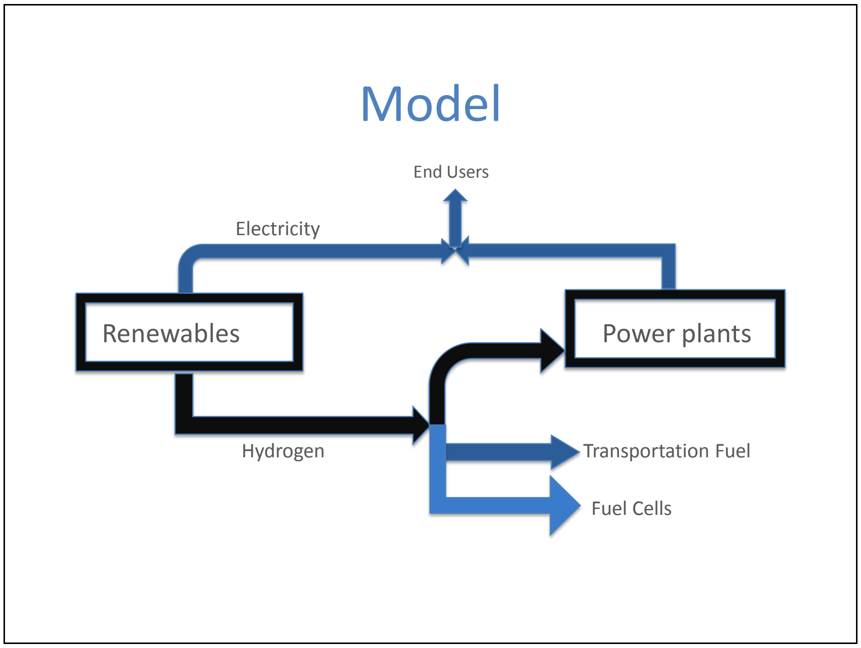

Figure 4: Model for Hydrogen generated from renewables

The current gas turbines run on natural gas. In order to use hydrogen in place of natural gas, some modifications are required to be made. Various companies in the power sector are developing hydrogen turbines. For the current power plants which use fossil fuels, technologies are already in place for carbon capture and sequestration. The carbon is separated from hydrocarbons and hydrogen is used in the turbines. Additional supply of hydrogen from renewables can be incorporated.

Successful integration of hydrogen in the above model involves the study of all stages starting from renewable resource assessment to the use of hydrogen in turbines. Hydrogen production, handling, transportation, storage and energy conversion processes are to be dealt with.

2. Hydrogen from Renewables

2.1 Resource Assessment:

We want to assess the resources in the United States to determine if enough hydrogen can be produced to meet the demands of the country. To make this determination, analysts at National Renewable Energy Laboratory determined the potential for hydrogen generation from photovoltaic (PV) and wind energy in the United States. Geographical Information System (GIS) data on solar and wind resources across the country were collected and combined with PV, wind turbine, and electrolyzer efficiencies and capacity factors to determine the amount of hydrogen that can be produced from renewable resources.

The PV energy data were calculated from average yearly solar data based on 40 km^2 land area grids.[4] The solar energy was converted to electricity via a PV non-tracking flat plate collector tilted at latitude. The study assumes any given 40 km^2 cell land area grid will have no more than 10% of its land area available for PV systems, and 30% of this area will actually be covered with PV panels yielding a total of 3% land coverage. In addition, the study excludes certain lands including all National Park Service areas; Fish and Wildlife Service lands; all federal lands with a specific designation (parks, wilderness, wilderness and study areas, wildlife refuge, wildlife area, recreational area, battlefield, monument, conservation areas, recreational areas, and wild and scenic rivers); conservation areas; water; wetlands; and airports/airfields. All of these land areas, plus a 3 km surrounding perimeter, are completely excluded: the water areas are excluded 100%. Furthermore, it is assumed that solar energy can be converted to electricity at an average system efficiency of 10%. Current PV efficiencies range from 10-15%, and with cell/module and inverter efficiency improvements could reach 15-20% in the next decade.

The wind energy data provide an estimate of hydrogen potential from wind for the United States based on wind sites that are categorized as Class 3 or better. With current technology, Class 4 and greater are considered economically viable, but for this study, Class 3 is expected to be viable in the near future and is included. The analysis used updated wind resource data that were

[4] Levene J.I., Mann M.K., et. al.- An Analysis of Hydrogen Production from Renewable Electricity Sources – NREL

available for several states. Where updated wind resource data were not available, low-resolution 1987 U.S. wind resource data were used. The grid cell resolution of these data varies from 200 m – 1 km for the newer high-resolution data to 25 km for the 1987 low-resolution wind data. The wind class of each grid cell was used to calculate the potential electrical generation for that grid cell by assuming 5 MW of wind turbines could be installed on each square kilometer. The following table of wind class capacity factors was used to calculate the actual potential electricity generation from each grid cell.[5]

Class	Capacity Factor
3	0.2
4	0.251
5	0.3225
6	0.394
7	0.394

Table 2: Wind class capacity factors

As with the solar data, environmental exclusion areas were defined as federal and state lands here wind energy development would be prohibited or severely restricted. The land exclusions account for transportation right-of-ways, locally administered parkland, privately administered areas, and proposed environmental lands. In addition, the following classes of land were excluded:

- 100% excluded are all National Park Service areas; Fish and Wildlife Service lands; all federal lands with a special designation (parks, wilderness, wilderness and study areas, wildlife refuge, wildlife area, recreational area, battlefield, monument, conservation areas, recreational areas, and wild and scenic rivers); conservation areas; water; wetland; urban areas; and airports/airfields.
- 50% exclusions were applied to the remaining Forest Service, Department of Defense lands, and non- ridge crest forest.
- Entirely excluded is the 3 km area surrounding 100% environmental and land use exclusions: does not apply to water exclusion.

Once the potential electricity production from wind and solar were determined, the hydrogen production potential could be calculated. The potential energy generation from PV and wind

[5] Levene J.I., Mann M.K., et. al.- An Analysis of Hydrogen Production from Renewable Electricity Sources – NREL

was combined with an electrolyzer system energy requirement to calculate the amount of hydrogen that could be produced from renewable resources across the United States. For this study 52.5 kWh/kg of hydrogen was assumed, which is a 75% efficient system based on the higher heating value of hydrogen. This efficiency is the entire efficiency of the system, including the electrolysis cell stack, any energy requirements from system auxiliaries and system losses.

2.2 Resource Analysis Results:

The results verified that there are abundant solar and wind energy resources to meet hydrogen demands for the entire country. The potential for hydrogen production from PV and wind for the entire country is 1,110 billion kilograms of hydrogen. The total electricity consumption of the United States in the year 2009 was 3,741 TWh. The gasoline consumption of the United States as a whole was 128 billion gallons of gasoline in 2000. As a kilogram of hydrogen is roughly equivalent to a gallon of gasoline in energy content, and also taking into account the energy content of hydrogen as well as average gas turbine efficiency of 58%, **we find that the total hydrogen potential from renewables in USA is about 8.6 times the total gasoline consumption or 6.7 times the annual electricity consumption of USA in 2009.** The figure below shows the potential for hydrogen production from solar and wind resources by county.[6]

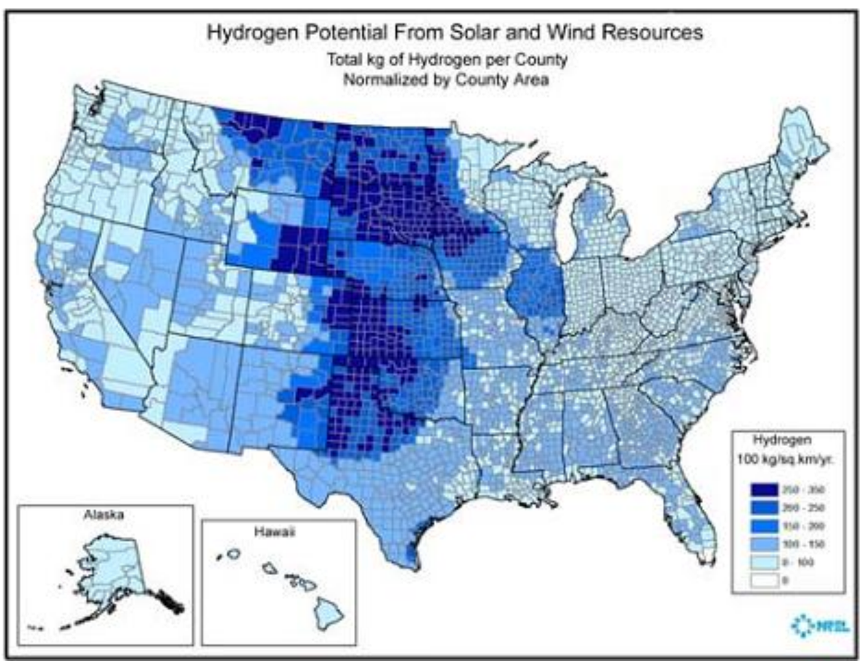

Figure 5: Hydrogen Potential (kg of hydrogen) normalized by county area.

[6] Levene J.I., Mann M.K., et. al.- An Analysis of Hydrogen Production from Renewable Electricity Sources – NREL

3 Hydrogen Production, Handling and Delivery

3.1 Hydrogen Production : Electrolysis

Electrolysis of water is the decomposition of water into oxygen and hydrogen gases created by the passage of electric current. If the electricity used is produced from renewable resources, hydrogen thus produced will also be from renewables.

3.1.1 Electrolysis: Technology[7]

Electrolysis of one mole of water produces one mole of hydrogen and half a mole of oxygen in their normal diatomic forms. Hydrogen will appear at the cathode and oxygen will appear at the anode. The process takes 54 -67 kWh of electricity per kg of hydrogen produced. The figure below shows the electrolysis process.

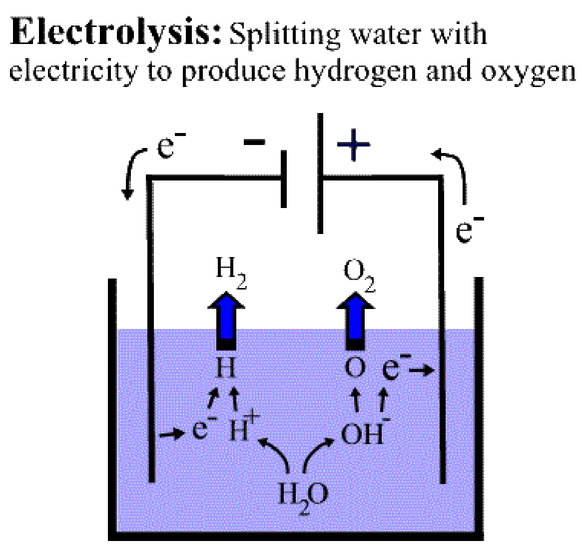

Figure 6: Electrolysis

3.1.2 Electrolysis: Cost

For renewables, the production cost accounts for 70% to 80% of the total hydrogen costs. If electricity is bought to run the electrolyzers, to bring price to $2 per kg of hydrogen produced,

7 Source: Wikipedia - Electrolysis

electricity prices should be lower than $ 0.012 per kWh as per 2004 technologies. If electricity is free, the lowest price for hydrogen that the 2004 electrolysis units can produce is $1.60/kg of hydrogen. This can be realized when the hydrogen production unit is integrated along with the renewable electricity system like solar PV, wind turbines, etc. This is more economical compared to a separate hydrogen production unit that purchases electricity produced by various renewables. Also the technological developments of electrolyzer systems should aim at improving efficiency of the system and reducing capital costs.

Reducing investment and operation costs is the main objective in the research and development of electrolysers. Elimination of exotic material on the electrodes (precious metal catalysts) and extending the lifetime by using electrodes with higher electrochemical stability are two approaches to lower capital costs. Since about two thirds of hydrogen production costs are caused by electricity, improving system efficiency has an outstanding relevance for electrolysis. For example, alkaline electrolyzers benefit from activation of the electrodes by a plasma arc process and membrane electrolyzers profit by improved catalysts, especially for the oxygen electrode. The table below shows typical costs of electrolyzer.[8]

- For an electrolyzer unit producing 1000 kg hydrogen per day

	Cost ($)	%
Capital Investment	2,241,141	28
Electricity	4,962,527	62
Operation & Maintenance	800,407	10
Total	**8,004,075**	**100**

Table 4: Costs of electrolyzers

[8] Saur Genevieve – Wind-to-Hydrogen project: Electrolyzer Capital Cost Study – NREL-2008

3.2 Hydrogen Handling

3.2.1 Liquefaction

Liquefaction of hydrogen is a capital and energy intensive option. The battery limit investment is $700/kg/d for a 100,000 kg/d hydrogen plant. Compressors and brazed aluminum heat exchanger cold boxes account for most of the cost. The total installed capital cost for the liquefier, excluding land and working capital is $1,015 /kg/day. Multi-stage compression consumes about 10-13 kWh/kg hydrogen.[9]

Gaseous crude hydrogen from the electrolyzer unit undergoes mulitple stages of compression and cooling. Nitrogen is used as the refrigerant to about 195°C (-320°F). Ambient hydrogen is a mixture 75% ortho- and 25% para-hydrogen, whereas liquid hydrogen is almost 100% para-hydrogen. Unless ortho-hydrogen is catalytically converted to para-hydrogen before the hydrogen is liquefied, the heat of reaction from the exothermic conversion of ortho-hydrogen to para-hydrogen, which doubles the latent heat of vaporization, would cause excessive boil-off during storage. The liquefier feed from the PSA unit mixes with the compressed hydrogen and enters a series of ortho/para-hydrogen converters before entering the cold end of the liquefier. Further cooling to about -250°C (-420°F) is accomplished in a vacuum cold box with brazed aluminum flat plate cores. The remaining 20% ortho-hydrogen is converted to achieve 99%+ para-hydrogen in this section.

3.2.2 Gaseous Hydrogen Compression

Gaseous hydrogen compressors are major contributors to capital and operating costs. To deliver high pressure hydrogen, 3-5 stages of compression are required because water-cooled positive-displacement compressors could only achieve 3 compression ratios per stage. Compression requirements depend on the hydrogen production technology and the delivery requirements. For the pipeline delivery, the gas is compressed to 75 atmospheres for 30 atmospheres delivery. Higher pressures are used to compensate for frictional loss in pipelines without booster

[9] Simbeck .D, Chang .E – hydrogen Supply: Cost Estimate for Hydrogen pathways – Scoping Analysis – NREL - 2002

compressors along the pipeline system. The gaseous hydrogen has to be compressed to 215 atmospheres to filtube trailers.

3.3 Hydrogen Delivery to the power plants

There are three hydrogen distribution pathways: cryogenic liquid trucks, compressed tube trailers, and gaseous pipelines. Figure 7 below shows that each option has a distinct range of practical application.

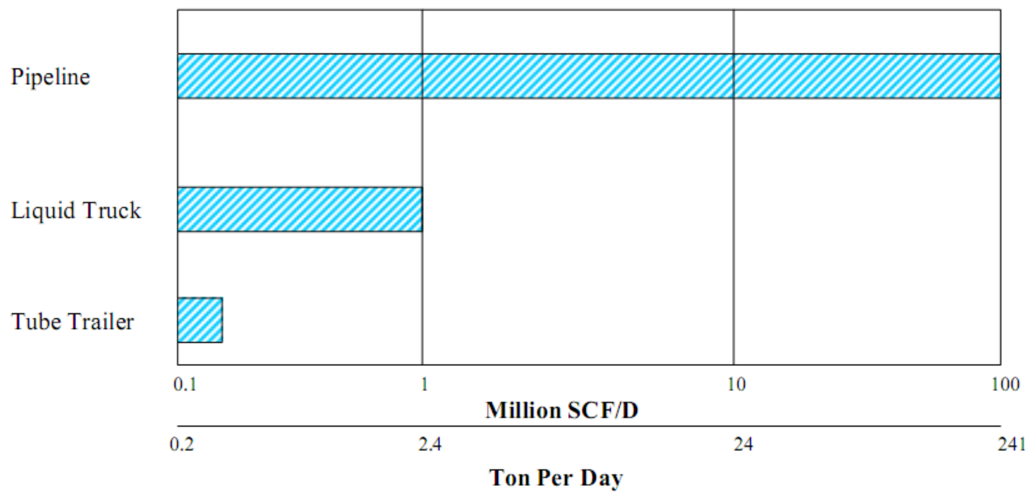

Figure 7: Hydrogen Delivery to the power plants

3.3.1 Road Delivery (Tanker trucks and Tube trailers)[10]

Based on the assumptions shown in Table below, the cost of liquid tanker truck delivery is about 10% of tube trailer delivery ($0.18/kg vs. $2.09/kg). Delivery by cryogenic liquid hydrogen tankers is the most economical pathway. They could transport relatively large amounts of hydrogen and reach power plants located at distant geographic areas. Tube trailers are better suited for relatively small quantities of hydrogen and the higher costs of delivery could compensate for losses due to liquid boil-off during storage. However, high-pressure tube trailers are limited to transport small quantities of hydrogen. Pictures of tube trailers and cryogenic tankers for hydrogen delivery are shown below.

[10] Simbeck .D, Chang .E – hydrogen Supply: Cost Estimate for Hydrogen pathways – Scoping Analysis – NREL - 2002

Figure 8: Tube trailer and cryogenic tanker

	Cryogenic Truck	Tube Trailer
Load, kg	4,000	300
Net delivery, kg	4,000	250
Load/unload, hr/trip	4	2
Boil-off rate, %/day	0.3	na
Truck utilization rate, %	80	80
Truck/tube, $/module	450,000	100,000
Undercarriage, $	60,000	60,000
Cab, $	90,000	90,000

Table 3: Road delivery comparison[11]

Typically, the tube-to-hydrogen weight ratio is about 100-150:1. A combination of low gaseous hydrogen density and the weight of thick wall, high quality steel tubes (80,000 pounds or 36,000 kilograms) limit each load to 300 kilograms of hydrogen. In reality, only 75%-85% of each load is dispensable, depending on the dispensing compressor configuration. Unlike tanker trucks that discharge their load, the tube and undercarriage are disconnected from the cab and left at the power plant. Tube trailers are used not only as transport container, but also as on-site storage. Liquid hydrogen flows into and out of the tanker truck by gravity, and it takes about two hours to load and unload the contents. It is estimated that the physical delivery distance for truck/trailers is 40% longer than the assumed average distance of 150 kilometers between the

[11] Simbeck .D, Chang .E – hydrogen Supply: Cost Estimate for Hydrogen pathways – Scoping Analysis – NREL - 2002

central facility and power plants.

3.3.2 Pipeline Delivery

Pipelines are most effective for handling large flows. They are best suited for short distance delivery, because pipelines are capital intensive ($0.5 to $1.5 million/mile). Much of the cost is associated with acquiring right-of-way. Currently, there are 10,000 miles of hydrogen pipelines in the world. The figure below shows a picture of pipeline for hydrogen delivery.

Figure 9: Pipeline for hydrogen delivery

Operating costs for pipelines are relatively low. To deliver hydrogen to the power plants at 30 atmospheres, the pressure drop could be compensated with either booster compressors or by compressing the hydrogen at the central plant.

Piping systems are usually several miles long, and in some cases may be hundreds of miles long. Because of the great length, and, therefore, great volume of these piping systems, a slight change in the operating pressure of a pipeline system can result in a large change in the amount of gas contained within the piping network.[12] By making small changes in operating pressure, the pipeline can be used to handle fluctuations in supply and demand, avoiding the cost of on-site storage.

[12] Amos, Wade A.- Costs of Storing and Transporting Hydrogen – NREL - 1998

4. Hydrogen in Gas Turbines

4.1 Hydrogen as a Gas turbine fuel

Hydrogen, as a carbon-free energy carrier, is likely to play an important role in a world with severe constraints on greenhouse gas emissions. In the power industry, its utilization as gas turbine fuel can be proposed under several possible scenarios, depending on the mode of hydrogen production. For instance, hydrogen can be produced remotely from renewable energy sources like solar or wind or from nuclear energy via direct thermal conversion or by electrolysis. In a near-term vision it will be derived from conventional fossil fuels by conversion processes including CO_2 sequestration. Possible solutions include remote coal conversion to hydrogen via gasification, shift, and separation from CO_2 and hydrogen pipeline transport to the power station. Integrated hydrogen and electricity production from coal or natural gas are also possibilities. Electricity can be generated from combined cycles integrated with fossil fuel decarbonization applicable to coal, oil, or gas and to CO_2 capture. Combined cycles coupled to hydrogen production/CO_2 sequestration processes can be proposed as a short/mid-term solution for massive greenhouse gas emission reduction.

For hydrogen produced from renewables and delivered to the power plants, some design modifications are needed to use it in existing gas turbines operating on natural gas. Many companies are doing research on hydrogen turbines. Some strategies like variable guide vanes operations, increased pressure ratio and re-engineered machines are being investigated to burn hydrogen in a large-sized, heavy duty gas turbine[13]. Dilution seems mandatory for using hydrogen in gas turbines. Steam or nitrogen dilution is possible. Efforts are made to reduce nitrogen oxide (NOX) emissions as well as to increase the efficiency of the system.

The first generation of future hydrogen-fired gas turbines will combust the gas with air. Just like in conventional gas-fired power plants, however, this process produces nitrogen oxides, which cause smog and acid rain. Emissions rise with the temperature, but so does the efficiency of the combustion process. The researchers are now simulating combustion processes to identify burner

[13] Chiesa .P, Lozza .G, Mazzocchi .L – Using Hydrogen as a Gas Turbine Fuel – Milano, Italy

concepts that generate the lowest possible emissions at the highest possible combustion temperatures.

One important lever is the flame, which propagates extremely quickly in hydrogen. The smaller and more stable is the flame, the fewer the nitrogen oxides that are produced. Trials with a recently developed swirl burner have already shown significantly reduced emissions.

4.2 Hydrogen in IGCC Power plants[14]

Combined cycle is an assembly of heat engines that work in tandem off the same source of heat, converting it into mechanical energy, which in turn drives the electrical generators. Exhaust of one engine is used as the heat source for another, thus extracting more useful energy from the heat, increasing the system's overall efficiency.

Integrated Gasification Combined Cycle (IGCC) is employed to convert coal, oil or biomass into gaseous fuel called synthetic gas or syngas. Synthetic gas is a mixture of carbon monoxide and hydrogen. The gas produced is cleaned up and fed into a shift reactor where water-gas shift reaction occurs. Carbon dioxide is formed and can be separated from hydrogen fuel. This process is usually accompanied by carbon sequestration method or enhanced oil recovery (EOR) method to capture and store carbon back into the earth's crust. Hydrogen fuel can be used in the combined cycle power plant to generate electricity. Moreover, hydrogen generated from the renewables can be externally fed into the combined cycle, thus utilizing hydrogen for electric power generation. The figure in the next page gives a schematic representation of the process.

[14] Todd D.M, Battista .R.A. – Demonstrated Applicability of Hydrogen Fuel for Gas Turbines – GE Power Systems

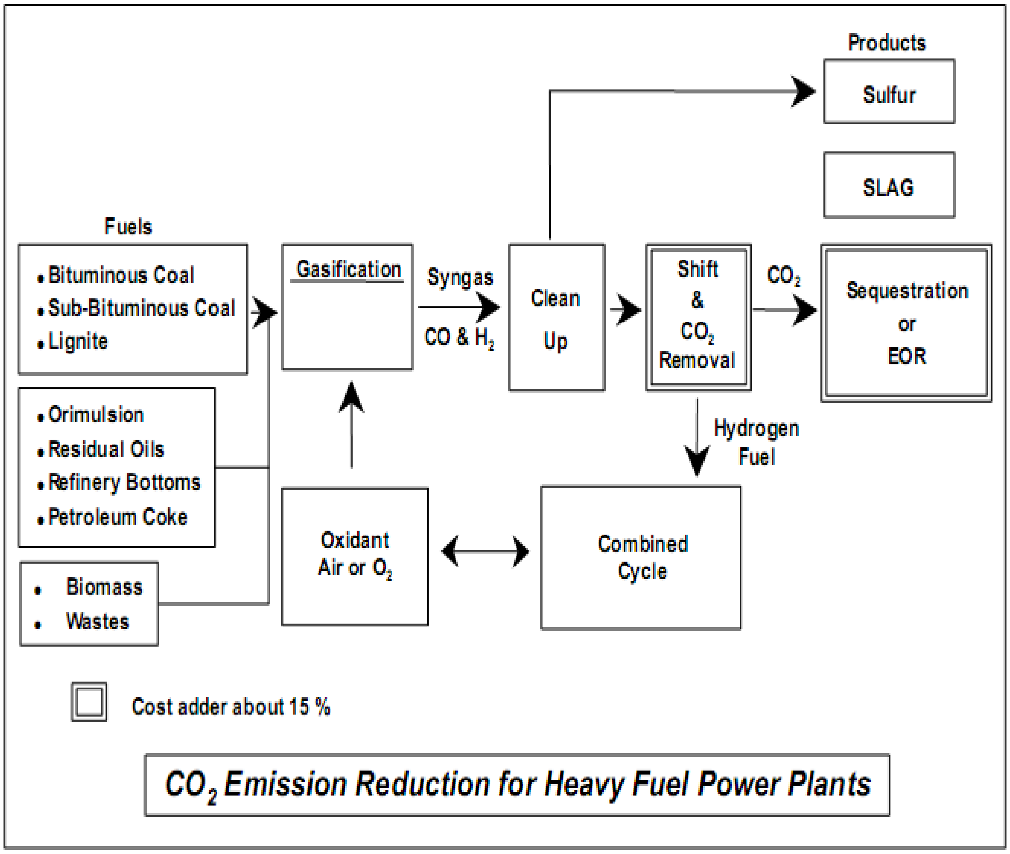

Figure 10: Integrated Gasification Combined Cycle

Since the gasification units are already in place at many power plants, the additional cost of shift reactor and carbon dioxide sequestration will be about 15% of the total cost.

4.3 Hydrogen in IRCC Power Plants[15]

Integrated Reforming Combined Cycle (IRCC) is employed to extract hydrogen fuel from natural gas and use it in generating electricity. The process involves a reforming unit that produces synthetic gas and the shift reactor that separates carbon dioxide from hydrogen fuel. Similar carbon capture methods are employed as in the case of Integrated gasification combined cycle. Externally produced hydrogen from renewables can be fed into the combined cycle thus utilizing hydrogen for electric power generation. The figure below shows a schematic representation of IRCC power plants.

[15] Todd D.M, Battista .R.A. – Demonstrated Applicability of Hydrogen Fuel for Gas Turbines – GE Power Systems

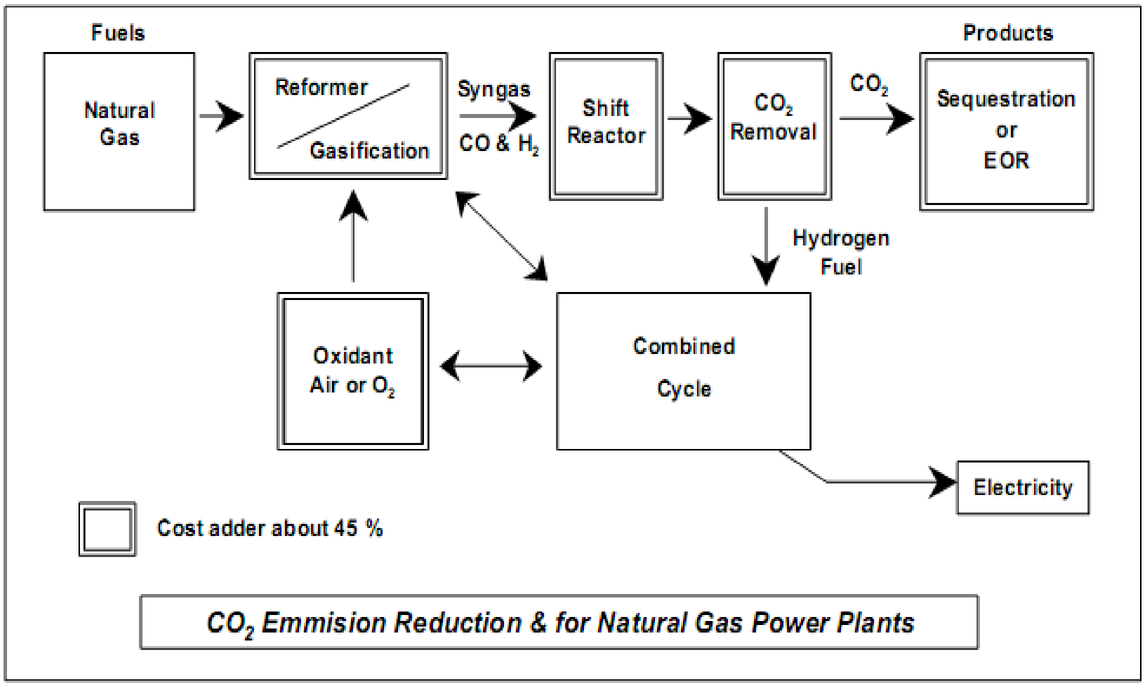

Figure 11: Integrated Reforming Combined Cycle

Since additional reforming unit has to be used along with shift reactor and carbon sequestration units, the cost incurred is more and is about 45% of the total plant cost.

5. Strategies for integrating Hydrogen in Power Sector

To integrate hydrogen into the present fossil-fuel-based electric power sector, various strategies are to be considered. There cannot be a sudden shift from depending on fossil fuel based methods of generating electricity to renewable energy based methods. But there must be a gradual but steady improvement in this process.

Temporary solutions exist in the areas of employing IGCC and IRCC methods that integrate hydrogen produced from the renewables as well as hydrogen produced from the fossil fuels. Efficient storage of electricity, particularly when the production is more than the demand during off-peak hours need to be addressed.

The following are some of the strategies to be considered for using hydrogen in electric power sector:

- Using already existing natural gas pipelines to transport hydrogen
- Centrally storing hydrogen in the power plants to ensure continuous hydrogen supply
- Production of hydrogen from the power plant itself during off-peak hours

5.1 Using Natural Gas Pipelines for transporting Hydrogen[16]

As discussed previously, the pipelines incur high installation costs. They are suitable for small distance transport if new ones are to be installed. But, it is possible to use already existing natural gas pipelines to transport hydrogen.

The transport of hydrogen gas under high pressure in steel pipelines has been common practice for more than 50 years. Such hydrogen pipelines, with a worldwide total length up to some 100 km, are in use. According to hitherto existing experience, natural gas steel pipes can be used to transport hydrogen as well for the following reasons:

- inside corrosion via embrittlement by hydrogen is not to be expected as long as plastic

[16] Beckervordersandforth C.P – Use of Natural gas Pipelines to Transport Hydrogen – Annex IV, Section 5 – Hydrogen Energy – R&D of Energy technologies

stretching due to unduly high strain can be avoided; this is guaranteed if observing the usual safety regulation of long distance pipelines.

- hardening of steel within the area of weld does not cause an increased susceptibility for embrittlement by hydrogen.
- outside corrosion on pipelines for natural gas as well as for hydrogen can be avoided by means of insulating wrapping, including the application of cathodic protection against corrosion.

5.2 Central Hydrogen Storage Unit in Power Plants

A central hydrogen storage unit in the power plant can be designed to store hydrogen supplied from different renewable sources and also to ensure continuous supply of hydrogen into the power plant. This also serves the purpose of storing electricity in the form of hydrogen. Whenever there is excess electricity produced during off-peak hours, electrolyzers can be employed to produce hydrogen within the power plant, which can be stored in the central unit.

Various methods are in practice to store hydrogen. However, for large-scale storage, an underground cavern, if available, can be used[17]. Also, using liquefiers will incur some additional cost but can store huge quantities of hydrogen in liquid form. The boil-off losses that occur can be utilized in supplying gaseous hydrogen to the power plants to generate electricity.

5.3 Hydrogen production from Power Plants during Off-peak hours

Storing electricity is a challenge in the present system. Batteries have limitations and are not environmental friendly. Hydrogen can be used to store excess electricity produced. Electrolyzers can be used to produce hydrogen from excess electricity, which in turn will be used as a fuel again to generate electricity whenever required. This will minimize the problems caused due to batteries as well as ensure efficient use of the already built central hydrogen storage unit.

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[17] Amos, Wade A.- Costs of Storing and Transporting Hydrogen – NREL - 1998

5.4 Flow model

The schematic below shows a typical power plant utilizing hydrogen derived from various reneable sources. The strategies discussed above are made use of in the schematic. Already existing natural gas pipelines are used. Other sources of hydrogen production are integrated in the same power plant by use of a central storage unit. During off-peak hours, hydrogen is produced by excess electricity from the power plant and stored in the central unit.

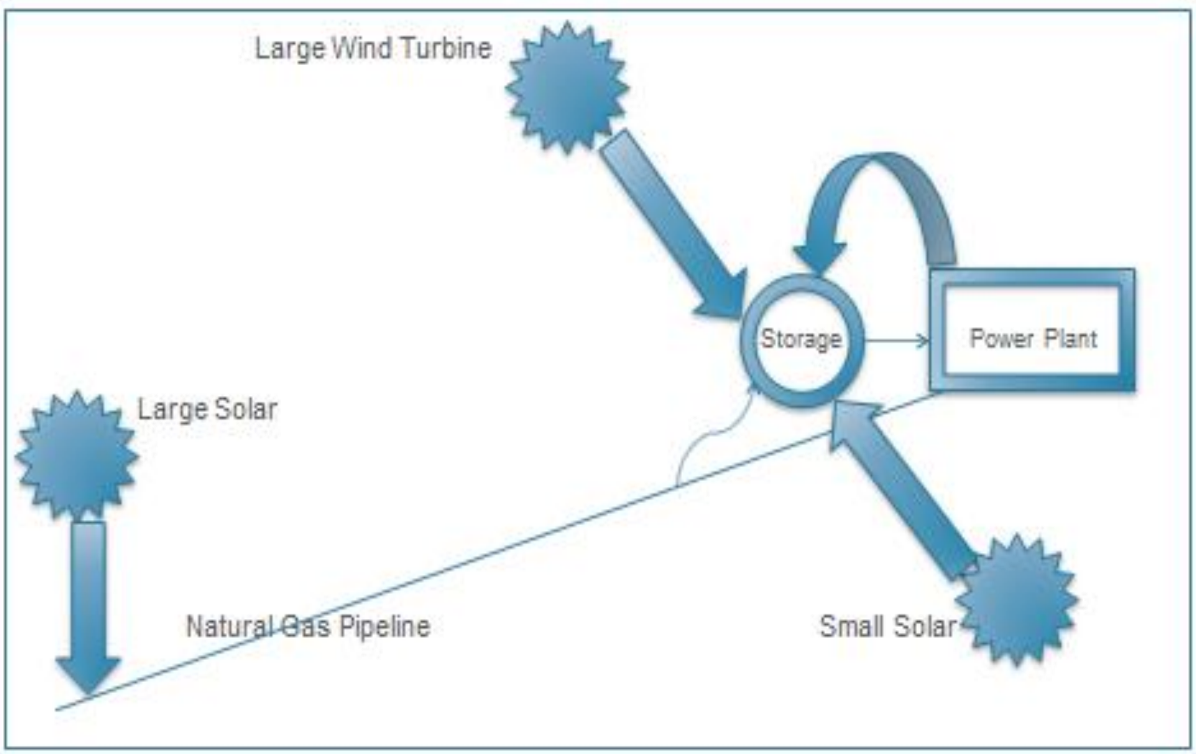

Figure 12: Flow Model

6. Conclusion

This study intends to promote the possibility of using Hydrogen in the Electric Power sector in the United States. The motivation for using hydrogen for electricity generation is derived from the fact that the electric power sector is the greatest contributor to green house gas emissions. This problem of emissions must be addressed immediately. Hydrogen serves the purpose as a source of clean energy.

The potential for producing hydrogen by making use of renewable energy sources like solar and wind are assessed. There is a huge amount of resource available to produce hydrogen. The resource assessment suggests that the potential available is much more than the energy consumption of the nation.

Various means of hydrogen production, handling and delivery to power plants are considered in the study. The suitability of the methods depends upon the production capacity of the hydrogen production plant.

For hydrogen to be used as a gas-turbine fuel, some design modifications are needed in the turbines, and this is still in the research stage. However, a temporary solution to integrate hydrogen in the turbines is available in the form of IGCC and IRCC power plants, which are discusssed in the study. Along with these modifications, some strategies are to be employed to better utilize the existing system and turn it gradually into a clean, renewable-resource-based electricity generation system.

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