International Journal of Innovation and Scientific Research
ISSN 2351-8014 Vol. 11 No. 2 Nov. 2014, pp. 312-321
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http://www.ijisr.issr-journals.org/

A techno-energetic review on hydrogen production using wind energy

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ABSTRACT: Renewable energy technology (RET) is gaining too much popularity now a day as these are considered as best replacement for fossil fuel based energy. Specially wind and solar energy gained much attention in developed as well as in developing countries. But one should also consider that these sources are not continuous, solar radiation is available at most 10 hours a day and wind also depends on particular geographical location. Due to their variable nature operator need to store energy from these sources so that power demand can be met during peak hours. But now during power oversupply, operators curtail these resources. The curtailment rates are expected to increase in future as RET shares increasing continuously.

Instead of curtailment one can store the energy but it is seen that storage is not as favourable as curtailment. So we suggest that instead of curtailment and storage in conventional electro-chemical battery system one should go for electricity storage in form of hydrogen. For this electrolysis is the best way. In this paper we will review the hydrogen production by electrolysis and its use in RET.

KEYWORDS: renewable energy storage, electrolysis by wind energy, wind energy storage option, curtailment vs. storage, hydrogen production.

1 INTRODUCTION

Nowadays, energy from renewable sources gained much more attention as these are considered as least carbon emitting sources and uses abundantly freely available resources. This paper describes how wind energy can be used for hydrogen generation. Paper starts with brief discussion on favouring this technology especially for the wind energy system. Then we move our discussion to basis of electrolysis. The objective of paper is to look into currently available these kind of technology.

Hydrogen is considered as clean fuel which can be directly use as fuel for IC engine or gas turbine, also hydrogen is having highest heating value which indicates its higher energy density. Theoretically water vapour is the only emission but due to high temperature NO_X is also formed but it can be controlled by ultra-lean operation of engine. Furthermore, hydrogen can be used in fuel cells for remote area and military applications. Currently most of the hydrogen is produced by cracking carbonaceous fuels. So this will further increase GHGs and emission. As a solution hydrogen production from RET seems to be best option available.

2 HYDROGEN PRODUCTION METHODS

Hydrogen is an energy carrier not an energy source. Hydrogen can be produced by several methods as shown in Figure (1), ranging from hydrocarbon fuels to water. *Water electrolysis* is one of the oldest and matured technology available for hydrogen production and it gives very pure hydrogen as compared to other methods but major drawback is that it uses electricity and it is an expensive process. A brief discussion on production technologies along with cost is provided by Timothy Lipman (2011). *Steam Methane Reforming (SMR)* is a process in which hydrocarbon derived gas is react with steam and produce hydrogen and carbon dioxide in presence of catalysts. SMR produces hydrogen rich gas (70-75%) along with carbon dioxide (6-14%), carbon monoxide (7-10%) and methane (2-6%) on a dry mass basis. In *gasification of coal and other hydrocarbons*, coal and other hydrocarbon fuels are partially oxidised, it yields a mixture of hydrogen and carbon monoxide. Hydrogen can also be produced from water by *Electrolysis process,* in which water is split into hydrogen and oxygen by using electricity in an electrolyser. There are several other methods like, *thermolysis, photolysis, bio-photolysis* etc.

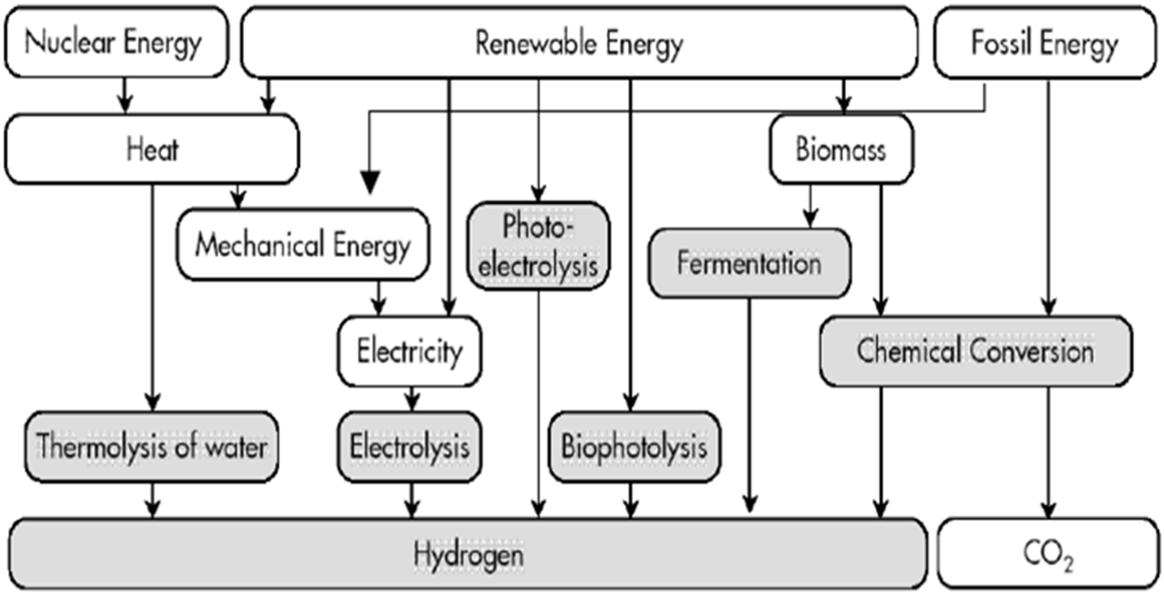

Fig. 1. Hydrogen production methods

3 REASONS FOR HYDROGEN PRODUCTION USING WIND ENERGY

Hydrogen can be produced by electrolysis which uses electricity; source can be anything like fossil fuel based electricity, solar PV, wave energy or any other resource. By using electricity from fossil fuel is worthless as it involves carbon emissions while generating electricity. Therefore, one should go for the RET for hydrogen production.

As RET, we have various technologies in which wind and solar PV dominate the world RET share. Wind power contribution is increasing at the rate of 30% annually and installed capacity was 238GW at the end of 2011[2]. Also if see with respect to India wind power installed capacity is 20298.83MW (Grid interactive power) by the end of January-2014[3]. While for Indian context solar PV based installed capacity is 2208.36MW (Grid interactive power) by the end of January-2014[3]. Their share expected to increase with supportive government policies.

These technologies provide a cleaner, sustainable and low carbon energy sources, but these technologies generate electricity from variable, weather-dependent resources.

In Figure 2 [4], variation of power demand and power generation by renewable (solar, wind and hydroelectric) with respect to time is shown. It is seen that with the assumption of the production is constant from midnight to 0800 h. It peaks from 0800 h to noon and falls rapidly thereafter till 1600 h. After that it decreases slowly till 2200 h and then is constant up to midnight. It is clear that there is a wide mismatch between the supply and demand curves. The supply is more than the demand for about 7 h from 9 a.m. to 4 p.m. when the sun is shining. For the remaining period of about 17 h, it is less than the demand. So during the power oversupply period there are two options; one is to store the energy and the other is to simply curtail the energy.

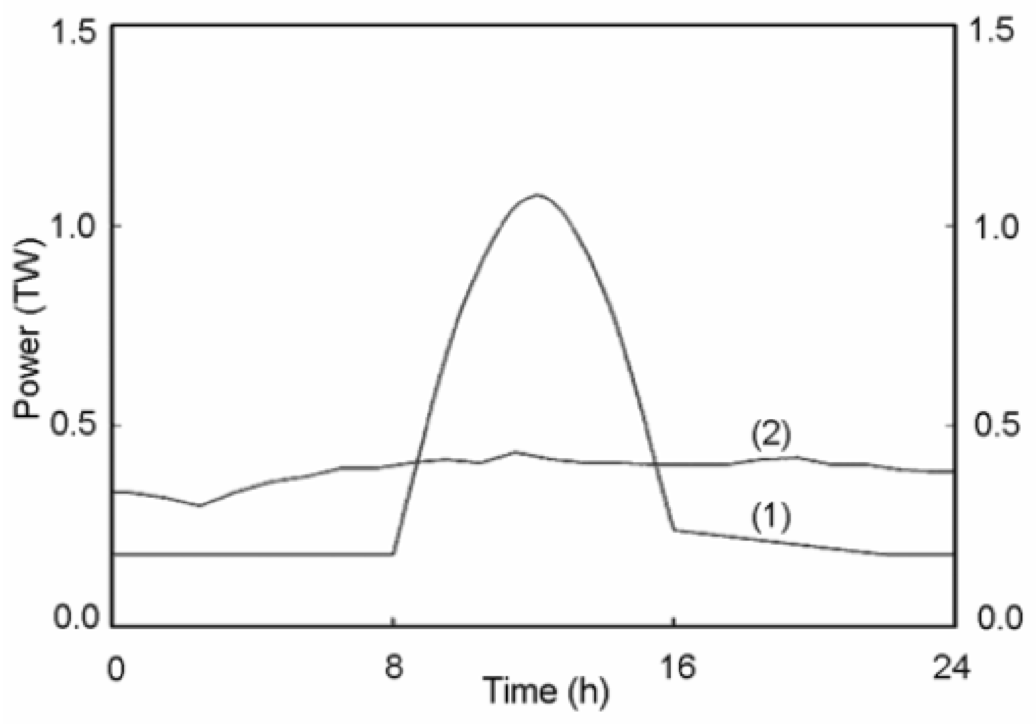

Fig. 2. Comparison of diurnal variation of production (curve 1) and demand (curve 2) over a typical sunny day.

Now moving our discussion towards the energetic side to evaluate under what conditions production of hydrogen is favourable from wind energy. In brief we are discussing the conditions under which energy from wind or solar PV should be store or curtail the oversupply. Charles J. Barnhart *et al.* (2013) [1] have derive the conditions for the same in their paper. They use an energetic model for the same, named Energy Return on Investment (EROI). It is the ratio of the energy delivered by a process/device to the energy used directly and indirectly in that process/device.

$$EROI = \frac{Life\ cycle\ energy\ delivered}{Life\ cycle\ energy\ invested}$$

Similarly ESOI is analogous to EROI, it is the ratio of electrical energy stored over the lifetime of a storage device to the amount of embodied electrical energy required to build the device. ESOI is specially defined for the purpose of comparison of different storage.

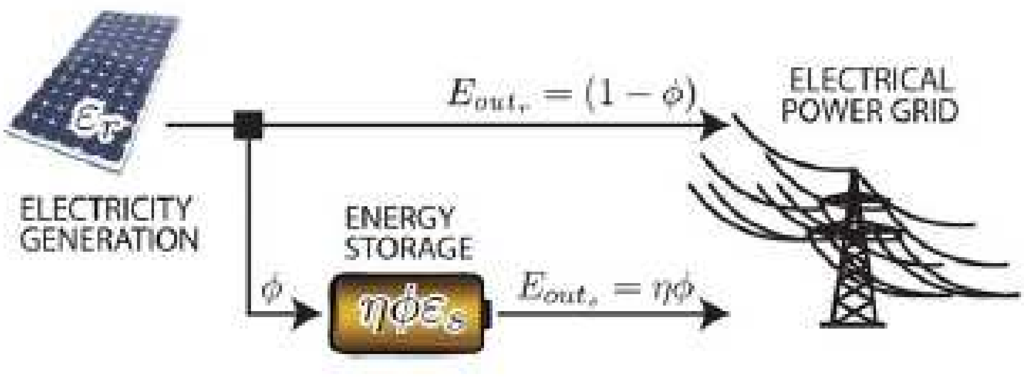

Fig. 3. Energy flow from RET [1]

If φ is the curtailed or store portion then for charging-discharging efficiency 100%, relationship between EROI and ESOI is given as:

$$\frac{ESOI}{EROI} = 1 - \phi$$

When this equality holds, curtailment and storage yield the same grid scale EROI. Otherwise, from an energy efficiency perspective, one of the two conditions exists:

(i) When $\frac{ESOI}{EROI} > 1 - \phi$ → In this condition one should store the electrical output from the renewable energy technology.

(ii) When $\frac{ESOI}{EROI} < 1 - \phi$ → In this condition one should avoid the storage, instead of storage curtail the generation of electricity from the renewable energy technology.

Graph (1) [1] shows the variation of EROI with respect to ESOI for different value of curtailment to storage fraction (φ) for equality relation. From this curve one can easily make decision regarding the whether to store or curtail the generation of electricity. Table (1) and (2) [1] provides data for different parameters used for ESOI and EROI calculation.

Table 1. Data used in NEA of variable resources by storage technologies.

Storage	η	λ	D (%)	ε_e	ESOI
Li-ion	90	6000	80	136	32
Nas	75	4750	80	146	20
PbA	90	700	80	96	5
VRB	75	2900	100	208	10
ZnBr	60	2750	80	151	9
CAES	70	25000	NA	22	797
PHS	85	25000	NA	30	704

Table 2. EROI Data for generation technologies

Generation	EROI
Wafer PV	8
Wind	86

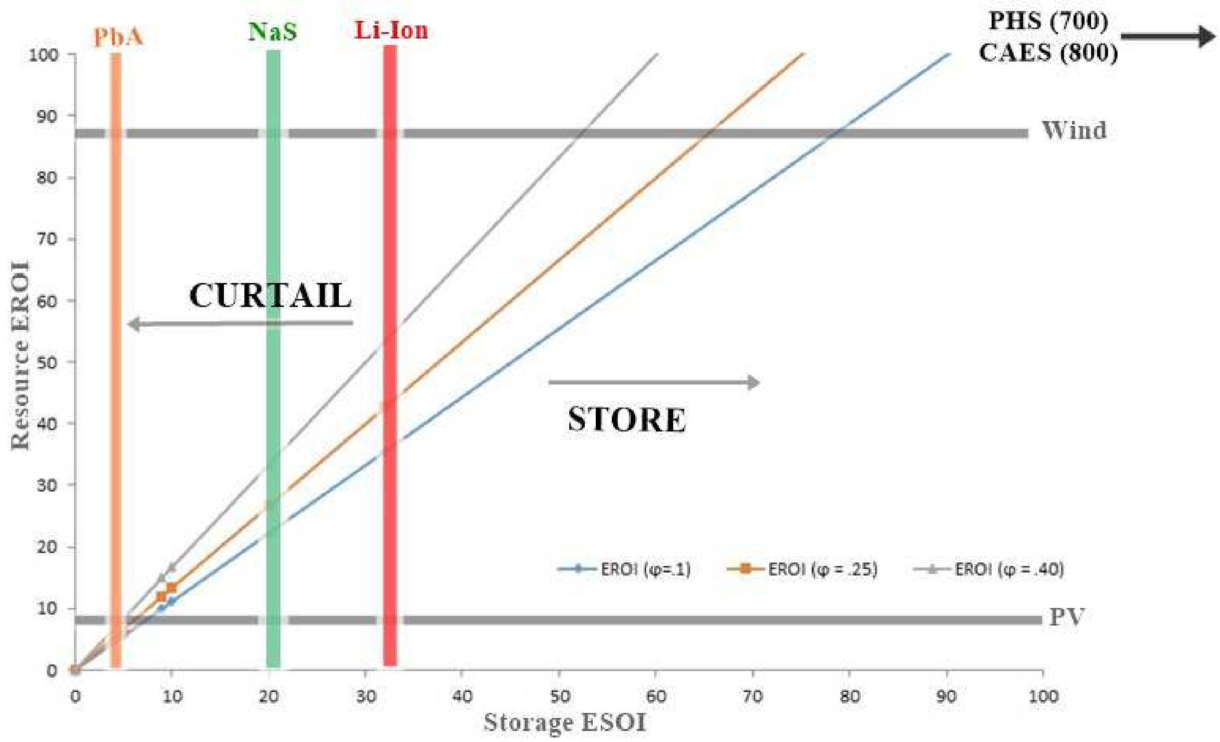

Fig. 4. Various combinations of resource EROI (y-axis) and storage ESOI (x-axis) for different value of curtailment or storage fraction (φ).

This plot simply tells that, from net energy perspective electricity generated using solar PV technologies can be stored efficiently using electrochemical based storage technologies like NaS, PbA, Li-ion etc. while wind power should be stored with more energetically favourable storage options such as compressed air energy storage etc.

Moving forward from this conclusion, that if someone wants to store energy instead of curtailment then instead of conventional battery storage one should use new technologies like PHS and CAES. In this paper we suggests that during oversupply one should use that energy from wind turbine and using electrolysis process produce hydrogen from locally available water and transport that hydrogen to near utilization point i.e. in Gas turbine or IC engine power plant.

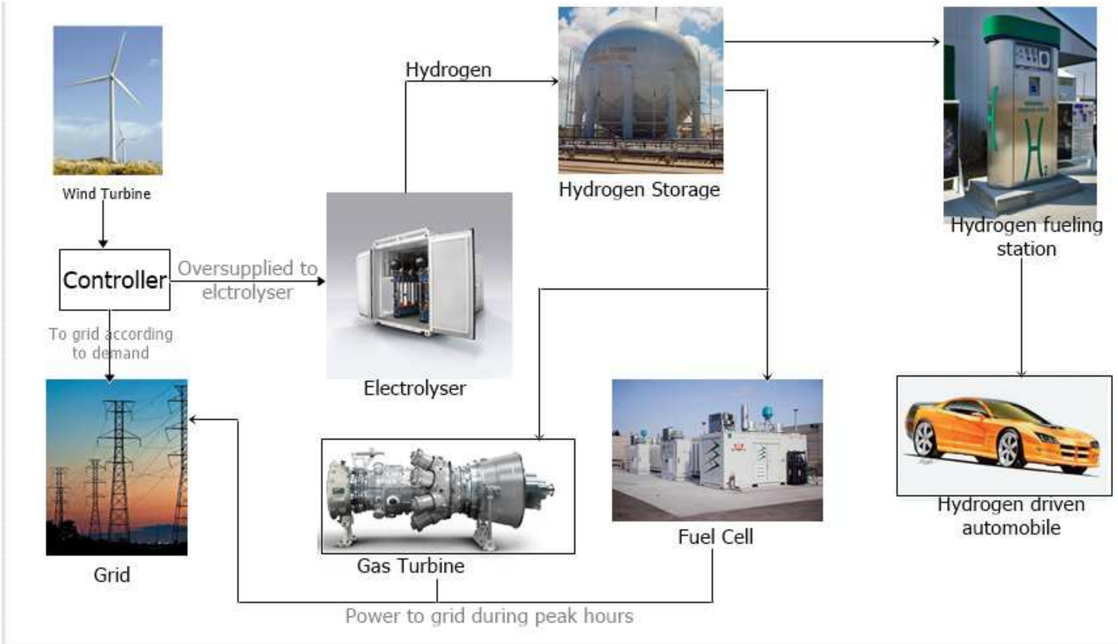

Fig. 5. A flow chart of Hydrogen production from wind and its utilization

We are encouraging hydrogen production by wind oversupplied energy, the reason behind is that hydrogen is clean fuel not only for a power plant but also for an automobile. Table (3) compares the various ignition properties for the Hydrogen as compared to other fuels which shares a major market share. Octane rating of Hydrogen is high so one can go for higher compression ratio to increase thermal efficiency. Flammability limit is also high so ultra-lean operation can be possible. Yet self-ignition temperature is high but it will ignite easily as minimum ignition energy is very small.

Table 3. Comparison of ignition properties for various fuels

Property	Hydrogen	Methane	Gasoline
Research Octane Number (RON)	>130	120	86-92
Flammability limit (in air, volume %)	4-75	5-15	1-7.6
Minimum ignition energy (mJ)	.02	.29	.24
Flame temperature (^{O}C)	2045	1875	2200
Auto ignition temperature (in air, ^{O}C)	586	540	230-500
Maximum flame velocity (m/s)	3.46	.43	-

Apart from this, ideally Hydrogen using power plant will emits water vapour only but in practical NO_X is also present which can be suppressed by ultra-lean operations.

4 BASICS OF ELECTROLYSIS

The most abundant source of hydrogen is water. Electrolysis is the most promising option for hydrogen production from RET. When used with renewable sources of electricity, it can produce hydrogen with zero or near zero GHGs emissions. As only water is used in the process, it can produce 99.995% pure hydrogen and oxygen. [5]

Water electrolysis is now developed technology, and it has been used for production ranging from a few cm^3/min to thousands m^3/h. It is relatively efficient (>70%), but because it need high grade of energy (i.e. electricity), hydrogen produced by this process is expensive. But as we shown above that wind power oversupply can be used for hydrogen production instead of curtailment.

An electrical power source is connected to two electrodes, or two plates (typically made from some inert metal such as platinum, stainless steel or iridium) which are placed in the water. Hydrogen will appear at the cathode (the negatively charged electrode, where electrons enter the water), and oxygen will appear at the anode (the positively charged electrode).

Assuming ideal faradaic efficiency, the amount of hydrogen generated is twice the number of moles of oxygen, and both are proportional to the total electrical charge conducted by the solution. However, in many cells competing side reactions dominate, resulting in different products and less than ideal faradaic efficiency.

In pure water at the negatively charged cathode, a reduction reaction takes place, with electrons (e^-) from the cathode being given to hydrogen cations to form hydrogen gas (the half reaction balanced with acid):

Reduction at cathode: $2\ H^+(aq) + 2e^- \rightarrow H_2(g)$

At the positively charged anode, an oxidation reaction occurs, generating oxygen gas and giving electrons to the anode to complete the circuit:

Oxidation at anode: $2\ H_2O(l) \rightarrow O_2(g) + 4\ H^+(aq) + 4e^-$

The same half reactions can also be balanced with base as listed below. Not all half reactions must be balanced with acid or base. Many do, like the oxidation or reduction of water listed here. To add half reactions they must both be balanced with either acid or base.

Cathode (reduction): $2\ H_2O(l) + 2e^- \rightarrow H_2(g) + 2\ OH^-(aq)$

Anode (oxidation): $4\ OH^-\ (aq) \rightarrow O_2(g) + 2\ H_2O(l) + 4\ e^-$

Combining either half reaction pair yields the same overall decomposition of water into oxygen and hydrogen:

Overall reaction: $2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$

The number of hydrogen molecules produced is thus twice the number of oxygen molecules. Assuming equal temperature and pressure for both gases, the produced hydrogen gas has therefore twice the volume of the produced oxygen gas. The number of electrons pushed through the water is twice the number of generated hydrogen molecules and four times the number of generated oxygen molecules.

The minimum necessary cell voltage for the start-up of electrolysis, E^o_{cell}, is given under standard conditions (P, T constant) by following equations:

$$E^o_{cell} = \frac{-\Delta G^o}{n.F}$$

Where, ΔG^o is the change in Gibb's free energy under standard conditions and n is the number of electrons transferred. In cell, change in volume is smaller as compared to that of pressure. Therefore instead of open cell (P, T=constant), we can assume it as closed cell (V, T=constant). So Gibb's free energy is replaced by the Helmhotz's free energy.

$$E^o_{cell} = \frac{-\Delta A^o}{n.F}$$

Where, $\Delta A^o = \Delta H^o - TR\Delta n - T\Delta S^o$

Analysing for, water electrolysis:

$\Delta H^o = 285.8\ kJ/mol,\qquad \Delta n = 1.5,\qquad \Delta S^o(H_2) = 130.6\ J/mol.K,$

$\Delta S^o(O_2) = 205.1\ J/mol.K\ ,\qquad \Delta S^o(H_2O) = 70\ J/mol.K\ \ ,$

$\Delta S^o_{total} = 130.6 + \frac{1}{2} * 205.1 - 70 = 163.14\ J/mol.K$

$\Delta G^o = \Delta H^o - T\Delta S^o = 237.2\ kJ/mol$, at STP

$\Delta A^o = 233.1\ kJ/mol$

Therefore, $E^o_{cell} = 1.21\ V$, for closed cell.

And, $E^o_{cell} = 1.23\ V$, for open cell.

For both the case, i.e. open and closed cell, the minimum necessary cell voltage for the start-up of electrolysis, E^o_{cell} is in the range of 1.2 V, which is easily achievable by a wind turbine.

Here we are presenting some data from commercial electrolysis systems *(Source: NREL, USA)*; the data of five companies' electrolysis units, commercially. For these systems, the water-to-hydrogen conversion efficiencies ranges from 80%-95% and hydrogen purities ranges from 99.8%-99.9998%. The system energy efficiency, defined as the higher heating value (HHV) of hydrogen divided by the energy consumed by the electrolysis system (system means electrolyser, rectifier and other auxiliaries) per kilogram of hydrogen produced, ranges from 56% for Proton company's Proton Exchange Membrane (PEM) process to 73% for Stuart and Norsk company's Hydro's bipolar alkaline systems. Other observations are shown in table (4) [6].

Table 4. Commercially available electrolysis units (Source: NREL, USA)

Manufacturer	**Technology**	**System Energy Requirement (kWh/kg)**	**H2 production rate (kg/yr)**	**Power Required for Max. H2 Production Rate (kW)**	**H2 Product Pressure (psig)**
Avalence	Unipolar Alkaline	56.4-60.5	320-3600	2-25	Upto 10000
Proton	PEM	62.3-70.1	400-7900	3-63	~200
Teledyne	Bipolar Alkaline	59.0-67.9	2200-33000	17-240	60-115
Stuart	Bipolar Alkaline	53.4-54.5	2400-71000	15-360	360
Norsk Hydro	Bipolar Alkaline (High Pressure)	53.4	7900-47000	48-290	~230
	Bipolar Alkaline (atmospheric pressure)	53.4	39000-380000	240-2300	0.3

5 REVIEW ON PRESENT RESEARCH

5.1 NREL'S WIND-TO-HYDROGEN PROJECT:

United States' primary laboratory for renewable energy and energy efficiency research and development NREL, in partnership with Xcel Energy, launched a wind-to-hydrogen (Wind2H2) demonstration project at the National Wind Technology Centre in Boulder, Colorado. The Wind2H2 project links wind turbines to electrolysers, which pass the wind-generated electricity through water to split it into hydrogen and oxygen. The hydrogen can then be stored and used later to generate electricity from an internal combustion engine or a fuel cell.

The *Wind2H2* project uses two wind turbine technologies: a Northern Power Systems 100-kW wind turbine and a Bergey 10-kW wind turbine. Both wind turbines are variable speed, meaning the blade's speed varies with wind speed. Such wind turbines produce alternating current (AC) that varies in magnitude and frequency (known as wild AC) as the wind speed changes.

The energy from the 10-kW wind turbine is converted from its wild AC form to direct current (DC) and then used by the electrolyser stack to produce hydrogen from water. The energy from the 100-kW wind turbine is monitored with a power transducer, and stack current on the 33-kW alkaline stack is varied proportionally. Apart from it, system has a10 kW photovoltaic modules (multi-crystalline) which gives DC power directly.

For hydrogen production, system has two HOGEN 40RE polymer electrolyte membrane electrolysers from Proton Energy Systems and one Teledyne HMXT-100 alkaline electrolyser. Teledyne produces 12 kg of hydrogen per day while HOGEN 40RE Electrolyser can produce 2.27 kg of hydrogen per day. Hydrogen gas obtained from the electrolysers is at 1034.2 kPa, for storage purpose it is compressed to 24.13 MPa with the help of hydrogen diaphragm compressor. Compressed hydrogen is then stored in the Hydrogen storage tanks (storing capacity is 85 kg at 24.13 MPa). This stored hydrogen is used to produce electricity during peak hour by an internal combustion engine. This small IC engine plant can produce 60 kW of electricity. There is a PEM fuel cell, which runs on stored hydrogen and it can produce 5 kW electricity, which can be used to meet peak hour's demand.

In 2009, NREL installed a new compressor, tank, and hydrogen dispenser to enable refuelling of fuel cell vehicles. From December 2008 through September 2009, NREL operated a Mercedes Benz F-Cell fuel cell vehicle. Hydrogen from wind and PV were compressed to high pressure to fill the vehicle's 1.8-kg storage tank. The vehicle travels around 110 miles between refuelling.

5.2 POWER TO GAS PROJECT

Power to gas [7] is a technology that converts renewable electricity into hydrogen or methane. The gas can be transported in the gas infrastructure and stored and then used in different application areas. If necessary, it is converted to electricity again. In this paper we are dealing with hydrogen production from wind energy mainly.

5.3 PILOT PLANT FALK HAGEN

Power to Gas is a similar project as of NREL's Wind2H2; storing surplus energy from renewable sources, such as solar and wind power, until it is required, balancing long-term fluctuations in generation. E.ON is building a pilot plant in Falkenhagen, Germany to convert excess wind power into hydrogen by electrolysis process. The hydrogen will be carried via pipeline to a connection point on the NG grid, where it will be injected into ONTRAS/VNG's high pressure transmission pipelines. The Falkenhagen storage plant will produce up to 360Nm^3/h of hydrogen from about 2 MW wind power through electrolysis. The hydrogen will be fed into the natural gas pipeline at around 2% by volume, at a maximum operating pressure of 55bar (gas), effectively storing and transporting renewable energy.

The work scope will include the engineering, construction, commissioning and start-up of a containerized 2MW electrolyser and compression plant. In addition the project will provide a power substation, metering station, hydrogen pipeline and natural gas grid access station. By storing oversupplied energy in the form of hydrogen which otherwise will be waste will increase the overall plant efficiency drastically.

5.4 RWE DEMONSTRATION PLANT

In this demonstration plant, 100 kW of electrical output is used with PEM electrolysis to produce hydrogen. The hydrogen produced in the plant is fed into the regional RWE gas network. With 100 kW$_e$ input, PEM electrolyser can produce 200Nm^3/h of hydrogen.

5.4.1 THÜGA DEMONSTRATION PLANT

This is an initiate of 13 companies at Frankfurt. In this demonstration project with 320 kW$_e$, 60 Nm^3/h of hydrogen is supposed to be produced which will be fed to the gas network with an operating pressure of 300 kPa.

5.5 EMERALD H2 AND NORFOLK WIND ENERGY

This project is solely intended to produce hydrogen from wind energy. A small fraction of that hydrogen, (< 5 %), will be used for fuel cell, capable of generating 1 MW of electricity during peak hours of electricity demand. The rest would be sold for use in a wide variety of industrial applications, from oil refining and chemical production to metals fabrication and electronics manufacturing. This plant of 10 MW wind facility that would annually produce more than 500,000 kilograms of hydrogen. This is about 20 times more hydrogen than a wind-to-hydrogen demonstration project in Boulder, Colorado of NREL.

Apart from above discussed projects, Sotavento Wind Farm [8] with rated 17.56 MW capacity is operational, there are feasibility studies are going on in various countries. LAîche-Hamane et al. [9] have estimated hydrogen production for an average wind speed of 7.5 m/s at 30 m height, 3900 Nm^3 for 10 kW wind turbine, 25350 Nm^3 for 50 kW and 99150 Nm^3 for 250 kW for south Algeria.

6 CONCLUSION

For wind energy oversupplied, battery storage is not recommended as discussed in previous sections. So we are suggesting hydrogen production and its storage. This stored hydrogen can be used to meet peak demand or fuel of an automobile. Most hydrogen is "reformed" from natural gas or other fossil fuels by stripping out the hydrogen atoms, a process that creates greenhouse gas emissions and eliminates some environmental benefits. Hydrogen is also produced through electrolysis using sources of electricity, such as fossil fuels, that generate air emissions. The hydrogen production from RETs allows researchers to explore how to make hydrogen without producing greenhouse gases or other harmful by-products. Yet there is embodied GHG with RETs but these are very small as compared to steam reforming methods. Therefore, hydrogen production from RETs should be encouraged instead of curtailment of energy.

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