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Economic assessment and prospect of hydrogen generated by OTEC as future fuel

Subhashish Banerjee, Md. Nor. Musa, Abu Bakar Jaafar*

OTEC UTM, Malaysia

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ABSTRACT

Hydrogen used for production of electricity through electrolysis using renewable energy systems is a costlier proposition. To date 96% of hydrogen production occurs from steam reformation of fossil fuels. Water splitting method from high temperature cracking, photo electrolysis, or biological decomposition processes, are in the research stage.

Life cycle cost analysis on hydrogen economy as transport fuel with fuel cell combine, including resolving its storage and transportation problems with cost of hydrogen production from power generated using different types of Ocean Thermal Energy Conversion (OTEC) plants, are evaluated. Scope of availability of hydrogen refuelling station from 100 MW (net power) OTEC plant could be determined.

Advancement in OTEC technology could help in developing 2nd/3rd generation plants (using solar hybrid OTEC; Uehara cycle). The scope of by-product availability can make its electricity production cost much cheaper and would make a viable proposition in producing OTEC powered hydrogen. This is suggested to resolve the challenges in hydrogen production economy.

Introduction

Economic advancement of countries have been identified from their quantum of energy use. Such energy sources to date are mostly from fossil fuels, mainly for their commercial viability. But this invokes not only the risk of global warming from huge carbon equivalent emission, but threatens sustainable development from depletion of the very fossil fuel itself, in not far off future. Present per capita emission of carbon equivalent has been estimated to be 1.1 metric ton as the global annual average [15]. With growing world population reaching 9 billion by 2050 [5], this carbon equivalent emission value is likely to reach 9.9 billion metric ton, with proportionate depletion of fossil fuel resources from their growing use to meet the economic growth. It has thus become necessary to find the best way to rein in emission and also to find viable alternate energy source that can provide economic growth with assured sustainable development, as well.

Abbreviations: BEV, battery electric vehicle; ECPB, electron coupled proton buffer; FC, fuel cell; FCEV, fuel cell electric vehicle; GHG, greenhouse gas; HER, hydrogen evolving reaction; IEA, International Energy Agency; ICE, internal combustion engine; LCCA, life cycle cost analysis; NG, natural gas; NREL, National Renewable Energy Laboratory; OER, oxygen evolving reaction; OTEC, Ocean Thermal Energy Conversion; PEM, polymer electrolyte membrane; PEC, photoelectrochemical conversion; PHEV, plug-in hybrid electric vehicle; RE, renewable energy; R&D, research and development; RO, reverse osmosis; OC-OTEC, open cycle ocean thermal energy conversion; SOTEC, solar hybridization with ocean thermal energy conversion; SR, steam reforming; TWh, terawatt hour.

* *Corresponding author*. 2 Diamond Park, Kohinoor Apt. Flat-10, Joka, Kolkata 700104, India.
E-mail address: wave.banerjee@gmail.com (S. Banerjee).

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In this context, use of hydrogen as the fuel source, that can be availed by splitting of water and also leaves behind nothing but water on its liberation of the energy, has been identified to be the future energy source in the new millennium. It ensures not only the energy supply and security, but also climate stewardship with ensured sustainability, with particular inclusion of transport sector providing mobile fuel [12].

It may be relevant to add in this context that hydrogen though an environmentally clean fuel, which leaves behind only water on its combustion with liberation of energy, is available only in the combined form with water or hydrocarbons. Hence, though its resource is almost inexhaustible it would always require energy input, either conventional fossil fuels or renewable energy for its production. Since it can be produced passing electric current in water, and can also be used to generate electricity through fuel cells hence it is considered to be instrumental in the storage of electricity, which unlike battery does not require periodic charging to derive power from it.

In view of the fact that hydrogen is a clean fuel with many advantages for sustainable growth, the International Energy Agency (IEA), started to promote hydrogen from 1977, with measures to meet the different challenges faced on its production from carbon free sources, as also sort out its storage problems and explore its scope of use as a clean fuel source [12]. But it has not yet achieved commercial success except for small scale trials as transport fuel, which still remains in the experimental stage.

It is thus needed to assess the present status of development on the prospect of hydrogen emerging as the future clean fuel, particularly the economic evaluation on its productions from the different types of renewable energy sources including Ocean Thermal Energy Conversion (OTEC) systems, and examine prospect of its use in different fields.

Based on the above discussions, it has been proposed to take up the following studies.

1. Present status on generation of hydrogen from different sources both in commercial scale as well as on indigenous R&D efforts on the same.
2. Its production from Renewable Energy (RE) sources including OTEC, as also from indigenous non-carbon sources, with their economic assessment.
3. Present day consumption of hydrogen generated from the above routes.
4. Economic evaluation of hydrogen for use as transport fuel.
5. Economic evaluation of hydrogen generated by OTEC power.
6. Scope of cost reduction of power generated from OTEC.
7. Aspects on hydrogen storage problems and their economy.
8. Identification of green areas of research for achieving economic gains.

A brief resume on above studies are appended below.

Present methods of production of hydrogen

Present production of hydrogen is mainly from the following six sources.

1. Steam reforming (SR) with coal.
2. Steam reforming of natural gas.
3. Steam reforming of naphtha.
4. Biomass decomposition.
5. Electrolysis of water.
6. Water splitting by various indigenous methods, like high temperature cracking, photo-electrolysis, or biological processes – though all these methods having promise are still in the R&D stage or, in pilot plant scale study only.

A brief resume of the above methods are stated below, including their merits and demerits.

Steam reforming with coal/gasification

Steam passed over heated coal under pressure with controlled amount of oxygen, breaks down yielding hydrogen along with other gases, like CO_2, CO. On scrubbing the other gases with appropriate reagents, hydrogen can be obtained by this gasification of coal in large scale, due to the scope of handling large amount of coal [15]. This process of hydrogen production leads to produce water gas, producer gas and synthesis gas.

Though economically viable, coal gasification process of hydrogen production gives rise to large amount of carbon equivalent gases, along with loss of huge coal reserve and is thus not a sustainable technology. Around 5 metric tons of carbon is emitted in the atmosphere per metric ton of hydrogen produced [1].

Steam reforming of natural gas (NG)

Hydrogen production through the route of steam reforming of NG is the cheapest method and is widely used. Though it does produce carbon equivalent gas emission, but is the minimum amongst all fossil fuel routes of hydrogen production [5]. In this process four parts of hydrogen is produced from one part of methane and two parts of water (steam injected) at high operating temperature and pressure, in presence of a catalyst and hence is a rather cheaper and efficient process of hydrogen production [15].

The reaction in the production of hydrogen is [18]:

$$CH_4 + 2H_2O = CO_2 + 4H_2;$$

in case of liquefied petroleum gas (LPG) it would be:

$$C_3H_8 + 6H_2O = 3CO_2 + 10H_2.$$

Its limitation however is not only carbon emission associated with it but its hydrogen conversion efficiency, as determined from the heating value of hydrogen produced. The energy input required to produce hydrogen is only 65–75 percent, against 80–85 percent achievable for hydrogen production by splitting water through electrolysis [15].

Naphtha/oil source

Oil route of hydrogen production is based on the use of steam reforming (SR) of Naphtha with low aromatic content. By this method steam at high temperature (>700 °C) is allowed to pass through naphtha in presence of a suitable catalyst, breaking the C–H bond producing hydrogen, as shown [18]:

$C_nH_{2n} + 2nH_2O = nCO_2 + 3nH_2$.

Such hydrogen production from oil refineries has been estimated to be 1.15×10^{10} ft^3 per day [15]. This value is equivalent to:

$(1.15 \times 10^{10} \times 0.02831685)$ m^3 per day $= 3.356 \times 10^8$ m^3 per day (since 1 cubic feet $= 0.02831685$ m^3).

Biomass origin of hydrogen production

Other than the above stated fossil fuel origin of hydrogen production, it may also be made through biomass origin as well. The process followed is either thermal gasification or pyrolysis, or by reforming at high pressure water-steam treatment; or by biological decomposition; or through chemical reaction routes – as shown below in Fig. 1 [28].

The biomass sources that are used for hydrogen production include both animal and agricultural residues produced. Common examples of such sources are: grass, vegetable, food processing waste, manure, sea plants and trees [15].

Gasification of biomass not only produces hydrogen, it also coproduces bio-fuels like, ethanol (C_2H_5OH). In fact, steam gasification of ligno-cellulosic biomass yields 17% of its weight producing hydrogen, two third of which comes from the water content of the biomass, and the carbon content of it is converted to water [28]. However, gasification of biomass for hydrogen production may be improved upon using suitable $Re/CeO/SiO_2$ based catalyst and using fluid bed gasifier for higher yield of hydrogen at lower temperature, at around 500 °C [28].

The highest yield of hydrogen is attained from gasification at 900 °C, the value of which is 71 g hydrogen per kg biomass [28].

Besides gasification, hydrogen production from biomass can also be done by dark fermentation reaction, using different enzymes or bacterial inputs to decompose biomass feed stock producing H_2 along with CO_2 and other gases. Limitation of such fermentation method is the low yield of hydrogen. Though theoretically hydrogen molar yield is supposed to be 4 mol H_2 per mole of cellulose or, sucrose or, starch. The laboratory output could not exceed above 2–3 mol of H_2, even using pure cultures of microbial inputs [28].

Electrolysis of water

In order to ensure sustainable development, it has been opined that electrolysis of water using RE generated electricity would play a dominant source of hydrogen supply in future [5]. With increasing pricing of fossil fuel resources, electrolysis of water is considered to be the only technically viable option, which with large scale hydrogen production can ensure terawatt hour (TWh) scale electricity production. Besides, hydrogen with fuel cell combination offers a method of storing electricity, and is more advantageous than battery for power storage which needs electricity to keep it operative and also require larger space than that of hydrogen as electricity storage option [5].

The hydrogen evolving reaction (HER) and oxygen evolving reaction (OER) occurs on electrolysis of water (passing electricity through it), as per the following reaction:

$H_2O \rightarrow ½O_2 + 2H^+ + 2e$; $2H^+ + 2e \rightarrow H_2$

In order to obtain better performance, polymer electrolyte membrane (PEM) is used. The advantage of using PEM is its scope of utility even in varied and intermittent power supply which may occur particularly on power supply from RE sources. The buffer used is ECPB (electron coupled proton buffer), typical example of which is Polyoxometalate Phospho Molybdic acid-$H_3PMo_{12}O_4$. Use of such ECPB buffer, decouples the OER from the HER, which allows oxygen and hydrogen to be produced separately in both space and time, allowing recovery of both hydrogen and oxygen [26].

It has been estimated that at 100% efficiency of the electrolyser, it would require 39 kWh with 8.9 L of water, producing 1 kg of hydrogen. But, with commercial electrolyser systems, having efficiencies at 56–73%, it requires 70.1–53.4 kWh to produce 1 kg of hydrogen at 25 °C and at 1 atmosphere pressure [28]. But as per the estimates made by Nihous and Vega [23]; 4.33 kWh is reported to produce 1 NM^3 of hydrogen (NM^3 = metre cube at normal temperature and pressure), which is equivalent to 48.5 kWh per kg. This value corresponds to the electrolyser efficiency of around 61%.

Hydrogen production from electrolysis gained importance from its scope of application as transport fuel and electricity generation from it through fuel cell route.

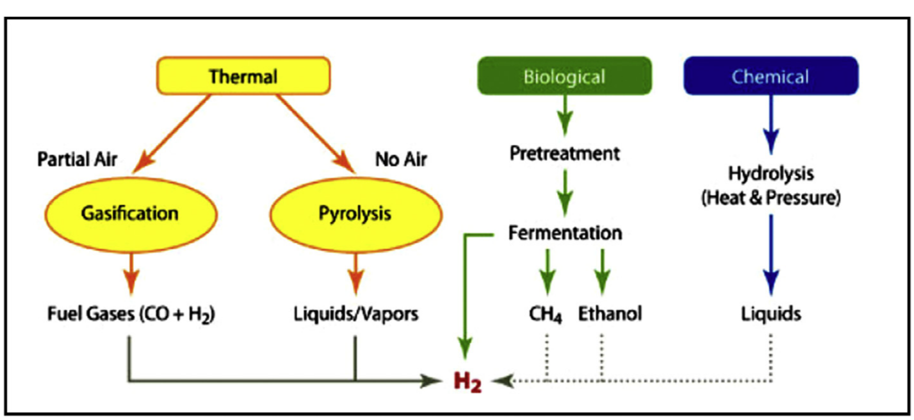

Fig. 1 – Different methodologies adopted for biomass route of hydrogen production. Source: [28].

It is relevant to add that it needs energy input to produce hydrogen by electrolysis. This energy input could be from renewable energy sources, like, wind, solar PV. OTEC, geothermal energy besides commonly produced electricity from fossil fuels.

Photolysis method of water splitting for hydrogen production

In addition to such splitting of water to produce hydrogen by electrolysis through energy input, splitting of water may also be effected from energy inputs, by other methods like, photolysis. Such photolysis may be either by photoelectrochemical method of water splitting or, photobiological method of water splitting. They are however in the R&D stage. A brief outline of them is reviewed on their present status of development.

In photoelectrochemical conversion (PEC), water is directly split to produce hydrogen upon illumination with solar irradiation [28]. The thermodynamic potential of water splitting at 25 °C is 1.23 V, whereas the commercial electrolysers run at 1.7–1.9 V (considering overvoltage loss etc.). The key issue to make the visible wave length region of solar spectrum suited to PEC method of water splitting possible, would be to avail suitable catalyst that can split the water using the energy of the visible range of the solar irradiation. In fact, under suitable catalyst combination, PEC method of water splitting using 10 percent solar irradiation covering an area of 4000 square miles can provide enough hydrogen to fuel the entire US fleet of 236 million vehicles [28].

The other route of photolysis to produce hydrogen by water splitting is photobiological method. Cyanobacteria and green algae can absorb 40–50% of the energy of sunlight. In fact, photobiological production of hydrogen has been linked to the light absorption and charge separation reaction of photosynthesis. Research groups worldwide are considering to combine photobiological and photosynthetic methods, for developing an integrated hydrogen producing system [28].

But, both these methods of photolysis-photoelectrochemical and photobiological methods of water splitting to produce hydrogen, are still in the R&D stage.

The different pathways of hydrogen production from RE sources is shown below in Fig. 2, though most of the present day methods of hydrogen production are through steam reforming of fossil fuels, percentage distribution of which are shown below in Table 1 and Fig. 3.

It would be obvious from Table 1 and Fig. 3 that out of 500 billion m^3 of hydrogen produced (at 25 °C and at atmospheric pressure), the contribution through electrolysis, using RE input is only 4%. Rest 96% of hydrogen production is through fossil fuel based methods, despite their limitations on sustainability, with depletion of fossil fuel and emission of greenhouse gases (GHGs). In fact, 2.5 metric tons of CO_2 is released for each metric ton of hydrogen produced from hydrocarbons, and 5 metric tons released when produced from coal [1].

Hydrogen production from application of RE systems with economy assessment

It may be important to note that most of the RE systems for hydrogen production (along with oxygen as well) has to go through electrolysis route, providing necessary electricity input as shown before in Fig. 2 [28]. Thus, electricity cost from

Table 1 – Global distribution of hydrogen production (as per 2000 data).

	Amount in billion m^3 at normal temperature and pressure per year	Percentages
Natural Gas (SR)	240	48
Oil (Naptha SR)	150	30
Coal(SR)	90	18
Electrolysis	20	4
Total	500	100

Source: [2].

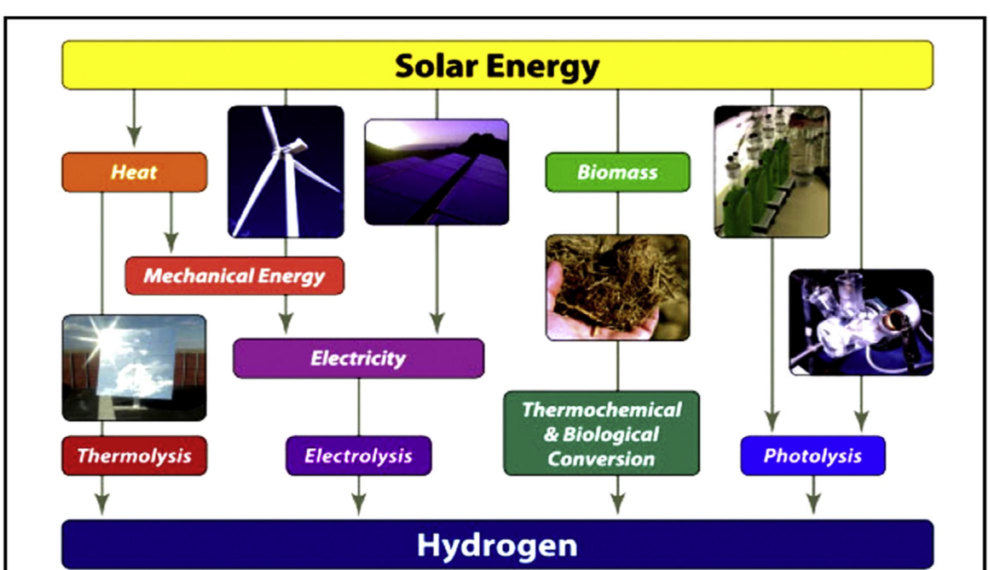

Fig. 2 – Different routes of RE systems of hydrogen production. Source: [28].

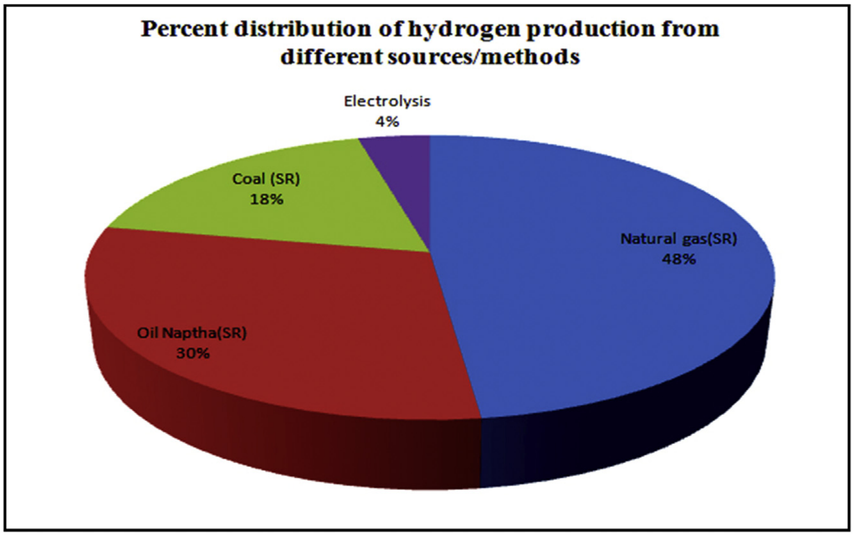

Fig. 3 – Percentage distribution of hydrogen production from different origins. Adapted from [2].

such RE sources has a major impact on its production economy [19]. It has been opined that electricity cost from solar PV and wind have to be four times cheaper, if they are to be competitive for the corresponding production cost of hydrogen generated from gasoline [1].

It may be added that biochemical decomposition from gasification, fermentation, pyrolysis, solar photolysis by photoelectrochemical or, photobiological method of water splitting to produce hydrogen, are independent of the electrolysis method. The former could not yet become economically viable, despite efforts of anaerobic indigestion of biomass and bio waste [1]. Economic success could not yet be achieved even from much older technology of methane production from biomass [1]. Also none of this biomass decomposition can be considered to be carbon free. On the other side, photolysis methods are still in the R&D stage though they have future promise.

It would be evident from the following Fig. 4 and Table 2, given below that the cost of electrolysis method of hydrogen production from RE sources is not economically viable, compared to the present most common methods (96%) of its production from steam reforming of fossil fuels. It would also be evident from the following Fig. 4 and Table 2, given below, that the energy requirement of hydrogen production by splitting water (electrolysis method) is much higher than hydrogen recovery from fossil fuel resources. Thus its production cost per kg shows much higher value than even from wind resource whose electricity production cost is considered competitive with fossil fuel based power generation; as shown below in Table 2.

It may be noted that of all the RE systems of hydrogen production from electrolysis route, it is the OTEC generated power which have the potential to be much cheaper than that from photovoltaic (PV) or wind, since its electricity production cost has the scope of lowering drastically from its various by-products availed free, along with its power generation [7]. Also the 2nd generation advanced OTEC plants with hybridization of solar energy (SOTEC) [29] and by using Uehara Cycle (instead of the commonly used Rankine cycle) not only the quantum of by-product availability (potable

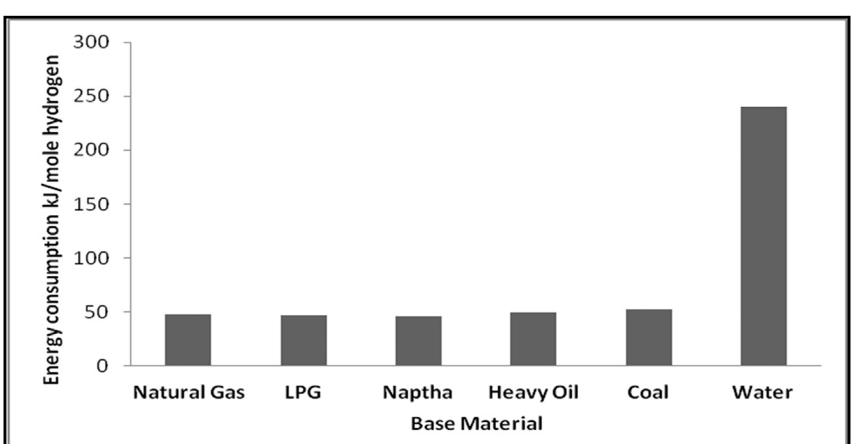

Fig. 4 – Energy consumption for hydrogen production from various sources. Adapted from [1].

Table 2 – Hydrogen production cost in \$/kWh from fossil fuel and RE sources [1].

Hydrogen production sources	Cost in \$/kWh (2003 data)
Natural gas reforming	1.03
Coal gasification	1.22
Gasoline based	0.93
Biomass gasification	4.63
Biomass pyrolysis	3.8
Wind electrolysis	6.64
Nuclear thermal splitting	1.63

water, mineral water, sea-food) would increase, but there would be appreciable improvement in its power supply efficiency [16].

However, attempts have been made to examine the scope of hydrogen production from power supply inputs of the present 1st generation OTEC of different sizes. In estimating the production volume and cost per kg of hydrogen production, the data cited by Nihous and Vega [23] has been adapted, which cites 4.33 kWh is needed per NM^3 of hydrogen production. Cost of electricity production has been determined estimating the levelised cost per kWh power generation as per the capital cost per kW net power values cited by Vega [27]; considering its capacity factor to be 90% with life of 30 years and at 8% discount rate. The data generated on hydrogen production volume and cost component (excluding the by-product royalty) for different sized and types of OTEC plants, based on the above premise are shown below in Table 3 and Fig.5.

It would be obvious that simultaneous O_2 production (by weight) would be 8 times the H_2 production from each of these OTEC plants. Also, in case of 100 MW OTEC plant the volume of H_2 produced would be:

$=16241404 \times 11.21 NM^3 = 182{,}066, 139\ NM^3$; (since 1 kg = 11.21 NM^3) [NM^3 = cubic metre at 273.15 K and at 100 kPa or, 1 atmospheric pressure]

It has been estimated that for use as transport fuel, hydrogen production of 1500 kg per day is needed in refuelling station feeding 250 cars per day [19]. In this context it can be shown that a single 100 MW OTEC plant (net power) can cater to around 30 such hydrogen refuelling stations. Of course the cost component is required to be improved upon, to compete with the present day cost of fossil fuels. This can be done from performance improvement and availing by-product royalty from OTEC plants over which it has immense scope as stated previously.

Despite the above future prospect of OTEC generated power input for economical production of hydrogen by electrolysis, it remains a fact that currently none of the available RE technologies has reached the state of development to

Table 3 – Hydrogen production from electrolysis for different OTEC plants.

Nominal plant size in MW	Capital cost in million \$[a]	Energy produced in MWh/year	Cost of electricity (\$/MWh)	Hydrogen produced/yr by electricity (OTEC) from electrolysis in kg	Cost of hydrogen in \$/kg excluding the cost of electrolyser
1.4(L)	58.19	11,038	572.33	227,388	27.78
5.3(L)	186.76	41,785	436.71	860,790	21.20
10(O)	240.71	78,840	298.32	1,624,140	14.48
10(L)	186.00	78.840	230.52	1,624,140	11.19
35(O)	420.00	275,940	148.72	5,684,491	7.22
50(O)	553.60	394,200	137.22	8,120,702	6.66
53.5(O)	451.01	427,194	104.48	8,800,394	5.07
100(O)	790.00	788,400	97.91	16,241,404	4.75

[a] Capital cost source: [27]; L = land based; O = off-shore plants.

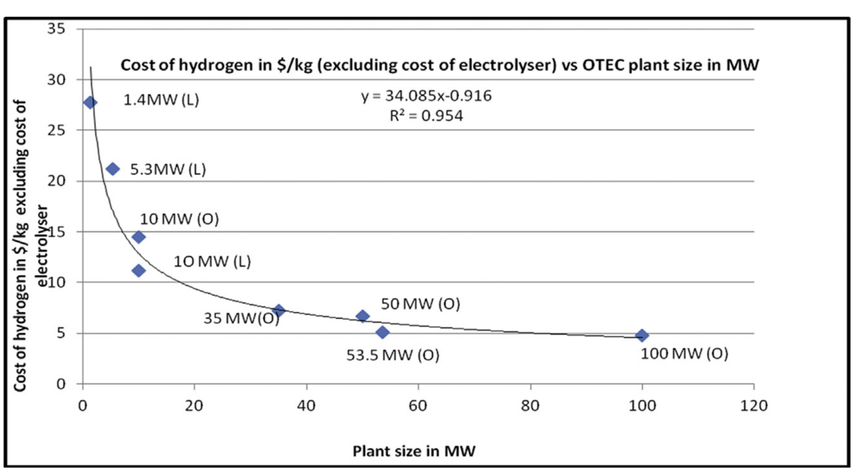

Fig. 5 – Cost of hydrogen generation by electrolysis from different type of OTEC plants.

replace hydrogen production with economic viability other than through fossil fuels routes [12].

Present day consumption of hydrogen

Present day use of H_2 is mainly confined to the production of H_2 rich chemicals, like NH_3, CH_3OH, and in oil refineries to make the crude oil from refinery to be used as transport fuel and also to make it cheaper. Hydrogen is added to crude oil (and also sulphur removal) to produce gasoline, diesel, jet, and other transport fuels; though their energy value from crude oil is lowered from lowering the carbon content with addition of H_2 [15]. Energy value thus lowered may vary from 95 to 80% from the crude oil, due to such H_2 addition with the crude oil in the refineries. It may be relevant to add here that heat evolved by burning carbon (graphite) to produce $CO_2 = 94{,}300$ cal; whereas for H_2 to produce $H_2O = 68{,}370$ cal; which is less by around 28% than that from carbon combustion.

Of course its primary scope of future use has been said to be its use as transport fuel through fuel cell technology. But present day production of hydrogen is only used to feed the refineries and chemical industries. In this context it may be useful to give an account on existing usages of hydrogen, shown in Table 4, the percentage distribution of which is compared in Fig. 6.

Table 4 – Global hydrogen consumption shares [1].

Category of use	Hydrogen consumed in billion m^3/year	Percentage of use
NH_3 production	273.7	61
Oil refineries	105.4	23
CH_3OH production	40.5	9
Others	13.6	3
Merchant users	16.1	4
Total	449.3	100

It could be noted from Table 4 and Fig. 6, that more than 90% of hydrogen production is used as raw materials for production of chemicals and not as fuel source. Of course both the chemicals NH_3 and CH_3OH, which together consumes 70% of H_2 produced, can also be considered as H_2 rich fuels with a better storage and transport system than H_2 itself [9,10,24]. 1 L of CH_3OH contains more H_2 than even 1 L of H_2 (liquid) itself even at −253 °C [24]. Same is the story with NH_3. As regards energy storage and transportation is concerned, NH_3 requires 5 times less energy for storage than that of H_2 and 3 times less energy for its transportation than H_2 [11].

It would therefore be needed to examine the scope of production of hydrogen from RE sources, including OTEC, with their economic assessment as well. Such production from application of RE sources could be either through electrolysis route, or from bio-chemical decomposition. The technology of photolysis methods is yet to attain the stage of commercial scale hydrogen production.

Economic evaluation of hydrogen for use as transport fuel

It has been projected by UAE that production of hydrogen from electrolysis using polymer electrolyte membrane (PEM) and thereafter electricity generation through fuel cell, would cost 90 percent of its electricity production by the turn of the century [15]. However, presently attempted alternate energy like, hydrogen/fuel cell route for use in vehicles are of the following types [5]. They are:

- pure battery electric vehicle (BEV) using different types of RE systems,
- fuel cell electric vehicles (FCEV) using hydrogen as fuel,
- plug-in hybrid electric vehicle (PHEV), which combine a battery system with an internal combustion engine or fuel cell system [5].

Though the technology for availing such vehicles excluding fossil fuel use may be available, but they are yet to be commercially viable, which perhaps needs further

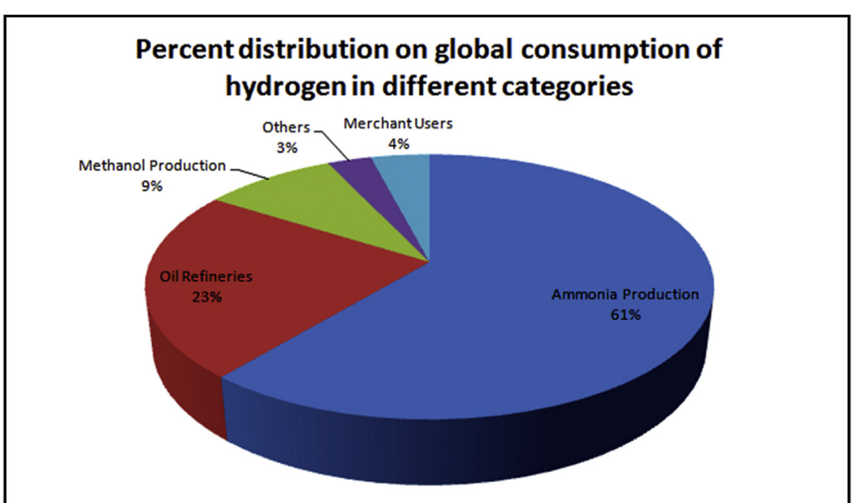

Fig. 6 – Global distribution percent of hydrogen consumption. Adapted from: [1].

improvement for attaining their economic viability. Their economic viability has also been vitiated for lack of enough skilled personnel to handle this new technology, as well as of not having enough hydrogen refuelling stations and thereby restricting the increased volume of use, which could have otherwise lowered their cost. This has thus created a "chicken and egg problem" stalling expansion of this new technology of fuel cell vehicles ensuring sustainable development [5].

There have however, been some attempts to build hydrogen refuelling stations at some places, like in Germany, Japan and California in USA [5]. Also, 16,000 km long pipe line to supply hydrogen has already been laid. But hydrogen transported thus is mainly used to feed the refineries and chemical industries [1].

Economy evaluation of hydrogen for use as transport fuel, based on the life cycle cost analysis (LCCA) study would involve not only the fuel production cost, but also include fuel transport cost as well as social cost considerations, if any [18]. Thus the detailed breakup of the above three points from LCCA study may be termed be as below.

- *Source -to-tank costs* (US $/functional units) = capital costs (e.g. production equipment, tank trailer, dispenser + Operation and maintenance costs (e.g. material costs, energy costs, labour costs) + other costs (e.g. tax, insurance).
- *Tank-to-wheel costs* = vehicle purchasing costs + operation and maintenance costs (e.g. fuel costs, maintenance costs) + others (e.g. tax, insurance).
- *Social costs* = the damage or prevention costs inflicted by GHGs and regulated air emissions.

Transport fuel cost of H_2-fuel cell combine could be developed based on the above model of LCCA. Fuel cell driven vehicles are run by the electricity generated by passing hydrogen through the fuel cell, as per Fig. 7 shown below. The hydrogen itself is however, required to be generated by passing electricity through an electrolyte, and may be from OTEC generated electricity, provided it emerges to be the cheapest method of electricity production.

Economy evaluation of OTEC powered hydrogen for use as fuel source

LCCA (life cycle cost analysis) studies on economic evaluation of OTEC powered hydrogen production would be the function of the following parameters, which expressed mathematically, may be written as below:

Total cost component of OTEC powered hydrogen production = $Y_c = f(C_l, H_s, H_t, Fe, F_c, S_c)$.

- C_l is the levelised cost of electricity of concerned OTEC plant [capital cost + operation and maintenance (O&M) cost included].
- H_s is the hydrogen storage cost.
- H_t is the hydrogen transporting cost to reach it to the user (varies depending on the storage methodology used and the modality of transportation).
- F_e is the efficiency of the electrolysis for generating hydrogen.
- F_c is the fuel cell efficiency for production of electricity, by passing the hydrogen as generated from the concerned OTEC plant.
- S_c is the social cost saving, as maybe accrued from use of hydrogen as the fuel, ensuring sustainability (by minimizing GHG emission and non-depletion of fossil fuel).

It may be relevant to assess the cost component, from the above 6 parameters, which contribute to the cost of hydrogen production. The most important of them are: C_l and H_s, which have immense scope of cost reduction. If found effective, it can ensure electrolysis route of hydrogen production to be economically viable at par, with the present day methods of steam reforming processes of fossil fuel based hydrogen

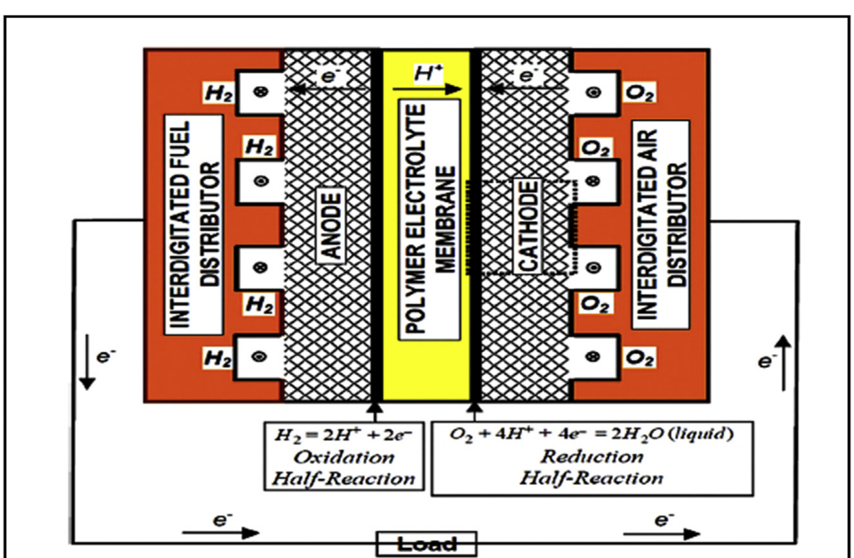

Fig. 7 – Polymer electrolyte membrane fuel cell showing hydrogen feed producing electricity. Source: [3].

production. It may even prove to be the cheaper option, when considered 'S_c', the saving of the social cost.

With this in view the scope of cost reduction of the above two parameters, C_l and $H_{s,}$ are discussed below.

By-products by OTEC which lowers the cost of OTEC plant

OTEC has the unique advantage of availing various by-products during its operation of power generation. This makes its electricity production cost much cheaper, from the scope of royalty as may be earned from these by-products. In addition it has immense scope of performance improvement, from development of the 2nd/3rd generation improved OTEC plants, as are likely to emerge in near future.

Banerjee et al. [8] showed from studies of different sizes of OC-OTEC (open cycle OTEC) plants, that in cases of OC-OTEC plants of sizes above 40 MW (net power), the electricity production cost can be appreciably lowered from the royalty earned from a single by-product potable water availed free. They opined that "this single by-product water, makes 100 MW OC-OTEC not only competitive with fossil fuel based desalination process; but saying the other way, as if the electricity generation is its by-product'' [8]. Besides, it can earn huge royalty with all types of OTEC plants, from the scope of production of mineral water (along with other by-products), as may be obtained by processing of deep ocean water (DOW) up-welled during OTEC operations [16].

It was shown by Vega [27] that the cost of electricity production from 100 MW (net power) OTEC plant is 11 cent/kWh, without taking into account the royalty earnings from its multifarious by-products. Banerjee [6] showed from necessary computation that the OTEC power generated from 100 MW (net power) plant involves capital cost $790 million. (as per computation from data provided by Vega [27]). If it is utilised for desalination then the cost of electricity will be $56.75/MWh for OC-OTEC (Open Cycle OTEC).

The production cost of desalinated water by RO process by fossil fuel is $0.6/m^3 [13] where as by OTEC it is $0.4/m^3. This indicates the OTEC generated power to be competitive with fossil fuels for desalination in potable water production, even with the present 1st generation OTEC plant.

Banerjee [6] also showed that the balance of plant cost or economic payback period of such 100 MW (net power) OTEC plants is 12 years, as estimated from the cash generated from the sale of its electricity production only. However, the multifarious by-products from OTEC helps in huge lowering of its electricity production cost.

The OTEC Spin off project (Okinawa in Japan) is said to earn annual revenue of $16.72 million, out of which 60% of the revenue ($10.032 million) is from the fisheries alone [21]. Banerjee [6] showed from estimations on earning of shrimp & prawn in China and Thailand, that even for 1% increment of such species from upwelling of nutrient rich cold bottom layer ocean water as needed for OTEC operation, it would make an annual extra revenue earning around = $ 675,00000, from these by-products alone.

In addition to enhanced growth of fish, the increment in growth of sea-weeds from OTEC operation have also scope of huge revenue earning, particularly because of sea-weeds' use as food (like Japanese Nori etc) as well as from their medicinal importance, known since Roman age (In. <http://oceanservice.noaa.gov/facts/seaweed.html> [9.10.2015]). Banerjee [6] showed that OTEC deployment with scope of increased growth of weeds as well, have huge potential of revenue earning, no less than that from fisheries.

Keeping in view the potential of such economic benefits even of the presently developed 1st generation OTEC plant, the commissioning of large scale OTEC plants are proposed, typical amongst which is the proposed 100 MW OTEC plant, to be commissioned by Lockheed Martin's in the coast of South China. In. <http://www.gizmag.com/otec-plant-lockheed-martin-reignwood-china/27164/> [8. 1. 2015].

Economic viability of OTEC gains ground not only from its prospect of earning huge royalty from the varied by-products as may be availed from OTEC operation; but also its scope of rendering services to the society and on social concerns, like cold storage/air conditioner (using up-welled cold bottom layer ocean water) without need of power, besides the sequestering of CO_2 from burial of increased marine species grown and thereby increasing oceans CO_2 dissolution capability.

In addition to the above stated prospects of economic gains as may be availed from the presently developed 1st generation OTEC plants, researchers have also identified its immense possibility of electricity cost lowering in its improved 2nd and 3rd generation types. It has been shown by Yamada et al. [29] from practical demonstration at ambient conditions in Kumejima Island, that just by using a single glazed flat plate solar collector of 5000 m^2 the annual mean thermal efficiency of the working fluid of OTEC plant can be increased 1.5 times. This boost of temperature from enhanced solar heating can thereby lower the electricity cost accordingly producing 1.5 times more electricity. OTEC cycle equipped with a flat plate solar collector making increase in solar radiation intensity have an additional advantage of decreasing the total exergy destruction rate of the system and thereby raising the exergy efficiency of the cycle and the production rate of hydrogen [4]. Using PEM electrolyser, the exergy efficiency of the PEM(Proton exchange membrane) electrolyser is about 56.5% while the amount of hydrogen produced by it is 1.2 kg/h. These approaches of developing improved 2nd generation OTEC, termed SOTEC, have thus immense possibility of appreciably lowering the electricity production cost from OTEC. SOTEC heats up the working fluid.

It has also been suggested by Japanese researchers in developing improved 2nd/3rd generation OTEC plants, where they proposed adoption of improved thermodynamic cycle for OTEC operations, like replacing the presently used Rankine cycle to Uehara cycle, which is basically a hybrid OTEC scheme ensuring production of potable water as by-product [16]. It has been claimed that such adoption would not only ensure 30–40% increase of performance efficiency of OTEC plants, but also assures doubling the potable by-product water production, from the present 0.5% of input SOW (surface sea water) feed to 1.0% [22,17].

Thus, 2nd/3rd generation of OTEC versions with the above stated advancements as are in the offing, can drastically reduce its electricity production cost suggesting OTEC powered hydrogen production by electrolysis to emerge as a viable economic proposition in future.

Aspects of hydrogen storage (Hs) and its economy

As stated before, hydrogen can be produced by passing electricity through an electrolyte. By passing the generated hydrogen through fuel cell, electricity can be produced. Thus production with storage of hydrogen provides a better method for storage of electricity (through electrolysis –H_2-fuel cell route); much better than the battery, since the latter has the limitation on requirement of power (for charging) to keep it operative. Thus storage of hydrogen is important being unanimous with the storage of electricity.

Hydrogen being the lightest element, loss from diffusion is a problem to reckon with. Thus, the period of storage and the frequency of its usage is important in making cost estimates. The technologies usually adapted for hydrogen storage and their costing, are as below [25].

1. **Compressed Gas storage system** – In such systems the gas is compressed to 20.7 MPa and stored in standard-pressure in (50-L) gas cylinders; but in spherical containers for storage of $H_2 > 15{,}000\ NM^3$. Cost of such storage system is $1.50–$4.20 per GJ.
2. **Liquefied form of hydrogen** – In this system of storage, hydrogen is compressed, cooled in a variety of sequences and stored as liquid H_2 at −253 °C. Because of such low temperature, loss from boil off is a concern, which can be 2%–3% per day for small vessels, but for large spherical type vessels it may be lowered to 0.1% per day. In case of large storage, cost is around $5–$8 per GJ.
3. **Metal Hydride system** – Metal Hydrides store hydrogen in the inter-atomic lattice of the metal. Such adsorption process (lattice hydriding) is exothermic, whereas the process of dehydriding whereby hydrogen is released from the hydride is endothermic – which requires heating to release the hydrogen adsorbed. Thus it is rather a safer process of hydrogen storage. Its cost component depends on the type of the hydride, and can be reduced if integrated with fuel cell. However normally its cost may be considered to be around $2.89–7.46 per GJ.
4. **Carbon based** – Activated carbon can reversibly adsorb 0.043–0.072 kg hydrogen per kg of it, at cryogenic temperatures 70–113 K and at pressures 4.2–5.4 MPa and the cost is around $3.50 per GJ. About one-third of such costing is required for the electricity spent for cooling and compression. NREL (National Renewable Energy Laboratory) however, reported the gravimetric storage capacity of 5–10%, even at room temperature, if carbon nano tubes are used for the storage of hydrogen.
5. **Chemical Hydrides** – Chemical Hydrides are useful for long time storage (>100 days). They include hydrogen rich chemical compounds like, methanol (CH_3OH), ammonia (NH_3), methyl cyclohexane. They are advantageous in transportation, handling and having better storage infrastructure. For vehicle refuelling of hydrogen from methanol cost is $29 per GJ, where cost of methanol itself is $11 per GJ. In case of ammonia, the cost of hydrogen generation is $38.9 per GJ, based on cost of NH_3 at $250 per metric ton.

Since each of these chemicals have their own specific methods of manufacture with hydrogen as the raw material, it is considered useful to make an elaborate discussion on the merits and demerits of these chemicals for hydrogen storage, particularly for methanol and ammonia.

Storage of hydrogen as methanol

Direct synthesis of methanol occurs by reaction of CO_2 with H_2, in presence of $CuO/ZnO/ZrO_2$ catalyst, as per the reaction:

$CO_2 + 3H_2 = CH_3OH + H_2O$; which is exothermic in nature. The reaction being reversible, the highest yield of CH_3OH can be obtained using the above catalysts with La, Cr and Ce as promoter, at 493 K [20]. CH_3OH thus produced from H_2, can yield H_2 by steam reforming process, which when fed to fuel cell would produce electricity.

It may be added as regards the advantage of storing H_2, converting it to CH_3OH, that amongst all the hydrocarbons CH_3OH has most H_2/Carbon. Even one litre of CH_3OH at room temperature has more hydrogen than even 1 L of liquid hydrogen at −253 °C, whereas the latter also has the disadvantage of losing 40% of potential hydrogen energy loss from liquefaction process, in addition to its loss from boil off at such low temperature, if required for longer storage period. Thus methanol is considered more efficient hydrogen carrier than hydrogen itself [24]. Methanol is thus considered the only liquid fuel, amongst all other hydrocarbons for use of fuel in vehicular fuel cell [24].

Thus, it has been suggested to use the production of hydrogen from power generated from OTEC to get converted to hydrogen rich compound like CH_3OH for its long storage, which is easily transportable to user.

Storing hydrogen as ammonia

Ammonia is produced using Haber-Bosch synthesis as per the reaction: $N_2 + 3H_2 = 2NH_3$, at operating temperature between 380 and 520 °C, and at pressure 12.0–22.0 MPa (Mega Pascal), in presence of a suitable catalyst of iron promoted with K_2O and Al_2O_3 [11]. Coal based ammonia production cost is lowest showing a value of $147–432 per metric ton; next comes natural gas based and OTEC power generated ammonia production cost, which shows a value of $689 per metric ton [11]. Comparing the two fuels ammonia and hydrogen, the former shows a remarkable advantage in storage and transportation than the latter. For hydrogen, transportation costs through pipe line is around $0.70–3.22 per kg, whereas for ammonia it is $0.0344 per kg [9,10].

Ammonia can have multifarious use, both as a fertilizer industry's mother chemical, as well as a hydrogen rich fuel. It can be used as a source of hydrogen for fuel cells to generate electricity. Its hydrogen content can be extracted by thermal catalytic decomposition or, electro oxidation. Also, ammonia is advantageous for its direct scope of use in fuel cells without the need of a separate reactor.

In. <http://www.intechopen.com/books/hydrogen-energy-challenges-and-perspectives/ammonia-as-a-hydrogen-source-for-fuel-cells-a-review> [30.9.2015].

Challenges to be met

It is a fact that hydrogen is considered to emerge by the turn of the century, as the future sustainable energy for production of electricity (through fuel cell route). It is also a fact that despite formation of bodies like IEA in 1977 to promote use of hydrogen as the fuel, it still remains an economically non-viable proposition [12]. Nearly 96% of hydrogen production is through fossil fuel routes and a very small percent, around 4% production is through electrolysis. Its use as transport fuel (considered to be the future fuel) is yet to achieve commercial viability and remains in experimental pilot plant scale projects only.

The main stumbling block in achieving economic viability is the present enhanced electricity production cost through RE systems, over which the production cost of hydrogen by electrolysis is dependent. In addition, there remains the problem of high leakage of hydrogen for its long time storage and transportation.

Despite some advancements achieved in cost lowering and efficiency increment of fuel cell technology and electrolysis—there remains scope of further efficiency improvements in these fields by R&D efforts.

Also, OTEC technology with its prospect of performance increment in its 2nd/3rd generation OTEC plants have immense scope, particularly in appreciable lowering of electricity production cost. This can be achieved from two fold approach. The first one is from production of huge by-products from OTEC and thereby from the earned royalty, electricity production cost can be appreciably lowered. The other is OTEC's scope of making improved OTEC schemes, introducing advanced thermodynamic cycle like Uehara cycle in place of Rankine cycle; as well as hybridisation of OTEC with increment of its working fluid, terming it to get converted to SOTEC. These two approaches are likely to make electricity cost of OTEC to the level of zero cost, if not negative.

As regards the storage and transport problem of hydrogen is concerned, the power generated from OTEC can be fruitfully utilised to make in situ production of methanol and ammonia, whose preference compared to compressed gas and liquid hydrogen have been elaborated in the previous section. Besides these, hydrogen enriched chemicals can directly be fed to fuel cell for power generation.

Thus it may be said that advancement in OTEC technology making its electricity production cost cheaper and scope of tapping the by-products of OTEC, goes hand in hand in resolving the economic stumbling block in hydrogen economy.

Conclusions

It could be concluded that though presently hydrogen's production through electrolysis seem to be economically non-viable, but OTEC power generated hydrogen with prospect of its huge by-product availability and prospect of development of 2nd/3rd generation OTEC plants, making its electricity cost drastically reduced, may meet the challenges in improving hydrogen economy.

Also its storage and transport problem may be resolved from the production of hydrogen rich fuels like, methanol or ammonia. With scope of improvement of fuel cell technology its use as transport fuel through hydrogen-fuel cell route in development of electrically driven car could be commercially viable in future.

The present day R&D studies in hydrogen production through indigenous processes like, photoelectrolysis, or biological processes have also future promise [14].

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