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# Application on Solar, Wind and Hydrogen Energy - A Feasibility Review for an Optimised Hybrid Renewable Energy System

**Subhashish Banerjee*, Md. Nor. Musa, Dato' IR Abu. Bakar Jaafar and Azrin Arrifin**

*Department of Renewable Energy, Universiti Teknologi Malaysia, Malaysia*

## Abstract

Present status of development of the energy systems, like solar, wind and of Hydrogen use as renewable energy sources, have been examined in ascertaining the scope of their application from techno-economic viability.

Efficiency rating of different generations of PV cells with cost component and scope of their use, including practical application and economic fall outs thereby, were also spelt out from case study. Cost of PV module being shown to be the main contributor, deciding the economy of PV – based power generation scheme, the methodology of determining its total requirement could also be shown. Economy evaluation of solar PV and solar heating (solar cooker, solar pond, etc.) were also assessed stating their merits and demerits.

Different aspects on evaluation of economy for off-shore and on-shore wind energy for developing a wind farm at a particular site were assessed. The scope of availing the wind energy value /sq. m. at a concerned site for a particular wind speed (measuring it at anemometer height and converting to its value at the hub height), could also be ascertained.

Necessary study on the economy of hydrogen production by splitting water (electrolysis) was made and was noted that the OTEC (ocean thermal energy conversion system) generated electricity would be the best cost-effective method, mainly because of its prospect of earning huge royalty from its different by-products. On examination of $H_2$-fuel cell combine as transport fuel, it could be shown that a single 100 MW OTEC can cater to 30 hydrogen refuelling stations, each with 250 vehicle movement/day.

Feasibility study on optimised hybridization of the combination of PV-wind and $H_2$, for uninterrupted power supply with methodology on resource assessment at concerned sites, particularly for PV and wind energy with economic fall outs, could be ascertained. Grey areas of research in exploring acoustic energy is also discussed.

**Keywords:** Solar energy; PV module; Solar pond; Wind energy; Wind speed; Off-shore wind energy; Hydrogen; Electrolysis; OTEC; Hybrid system; Acoustic energy; Piezoelectric effect

## Introduction

Sustainable development would require transition from fossil fuel based procurement of energy to renewable energy (RE) development. But total transition from fossil fuel to renewable energy is becoming difficult, mainly because of the economic constraint coming in the way of their large scale application. However, considering the problems faced on fossil fuel use, from the depletion of this very resource itself, as well as of environmental degradation from carbon equivalent gases emission inducing global warming, RE systems may emerge to be competitive with fossil fuels, if the social cost of the latter are taken into account.

In this context, Solar and Wind energy systems are the two most important source of renewable energy which has become very popular in recent times. They are being tried to develop with constant improvement of cost component from R and D studies and trials with necessary subsidies. In fact, in order to assess any energy system's commercial acceptability, its economic evaluation is very important for its further development as also for availing the research funding. For several decades extensive research work are being done on these two renewable energy systems for advancement of their technology. As a result of these R and D efforts their application cost have also fallen down. Another reason for their decreasing trend of cost is the increment of their volume of use.

The other RE energy which is being considered to be the most favoured energy by the turn of the century, particularly as the transport fuel, is the Hydrogen/ Fuel cell system. Hydrogen is important not only because it is an easily transportable clean energy. But it can be used to store electricity, producing it by electrolysis using electricity, and thereafter it can be used to produce electricity through fuel cell.

With this in view it is proposed to study the present status of development of these energy systems from the following perspectives. They are:

- The theoretical basis of their operation on electricity production.
- The brief review of their technology with emergence of cheaper and more acceptable 2nd and 3rd generation system.
- Suitable site of their implementation.
- Their efficiency and scope of use with economic evaluation

***Corresponding author:** Subhashish Banerjee, Department of Renewable Energy, Ocean Thermal Energy Centre, Universiti Teknologi Malaysia, Malaysia, Tel: 6-03-26154882; Fax: 6-03-26154283; E mail: wave.banerjee@gmail.com

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- Environmental fall outs including LCA studies on GHG emission etc.
- Limitations.
- Scope of further improvement with hybridization etc.
- Grey area of research

A brief review on above aspects on energy systems, Solar and Wind and Hydrogen type fuel, have been outlined below with feasibility study of their hybridization.

## Solar Energy

Most of the energy available--including the fossil fuels, owe their origin directly or indirectly, from the sun. The upper atmosphere of the earth receives from the sun more than $1.5 \times 10^{21}$ watt- hour of solar radiation annually, which is more than 23,000 times the energy used by human population globally [1]. Even if much less than 0.1% of this energy could be used effectively, it would meet the entire global demand of energy many times over.

In fact, direct tapping of solar radiation may be made, either by the generation of electricity from photovoltaic effect of incident solar radiation – using solar cells, or utilizing the heating effect of the solar insolation.

### Solar cells

**Theoretical basis of electricity production from solar PV cells:** Solar PV cells are basically semiconductor materials. It conducts electricity only when light falls upon the solar PV cells; otherwise it behaves as a semiconductor. Hence, they are termed photo-voltaic cell or, PV cell. Over 95% of the solar cells that are produced are Silicon (Si) based. This is because Si is abundantly found in nature. At the same time for processing, it does not put much burden to the environment. For making the solar cells, which is a kind of semiconductor, it involves doping them. Doping means that it is to be contaminated with certain elements that will allow flow of electricity. Such doping with selective chemical elements, produces either excessive positive types of charge carriers (p-type semiconductor), or negative types of charge carriers known as (n-type semiconductor). If both these type of semiconductors are combined, then p-n junction occurs at the boundary of the layers. As a result an interior electric field is built up which leads to the separation of the charge carriers. When light falls on them, then they are released, and on making metallic contacts, generation of electricity from electric charge flow, can be achieved. But the current build up thus made, is DC. A typical such type of PV cell, showing flow of DC current is shown below in (Figure 1) [2].

**Emergence of improved types of solar cells:** There are three categories of Solar PV Cells, mainly classified as the three generation cells.

- The first generation cells are single as well as polycrystalline silicon cells.
- Second generation cells are polycrystalline thin film crystal structure cells; amorphous Si: H cells, etc.
- Third generation cells are high efficiency multi -junction concentrator solar cells; like, dye sensitized cells, organic cells, polymeric cells, nanostructured cells including multi carrier photon cells, quantum dot and quantum confined cells. They are all of the third generation PV cells [3].

The 1st generation single crystalline Si cells occupy 31% of the market and its efficiency is as high as 24.7%. However it is expensive and require very pure silicon, like 99.999999999% pure silicon. Its processing requires long time and high temperature [3].

Second generation polycrystalline cells are fastest growing technology and have efficiency a little less. In case of second generation technology, it requires lower material use, fewer processing steps and simpler manufacturing technology. Hence it has cost advantages over the 1st generation crystalline Si: PV cells. The major systems in this 2nd generation of flat plate thin film PV cells are: amorphous Silicon (a: Si), Cadmium Telluride (Cd: Te), Copper Indium di-Selenide (CIS). Though they are cheaper than the 1st generation PV cells, but their efficiency is lower, around 13%. They occupied 15%-20% of the market in the year 2010 [3].

The efficiency percent of different types of 2nd generation Silicon based cells are shown below in (Table 1) [3].

On the other side, the third generation PV cells are high efficiency concentrator cells consisting of Gallium Arsenide substrate (Ga: As). They are twin junction cells with Indium Gallium phosphide made on Gallium Arsenide wafers. Their laboratory scale efficiency is around 40%. Dye sensitized PV cells, Organic PV cells and Nano structural solar cells are included in this category of 3rd generation PV cells. They are however, in the R and D stage and not yet realized experimentally [3].

**Application of Solar PV cells:** P-N junction of PV cell produces 0.5 V/cell. Agglomerate of a number of cells constitute a solar module, and multiple modules make array of PV cells, as shown in (Figure 2) given below [4].

As early as in 2000, at an inaccessible small island, in Sundarbans, India, (Gayenbazar in Sagar Islands, Sundarbans, WB, India) a PV array containing 320 modules of PV cells, with 36 solar cells in each module was installed, which provided 100 watts of power to 93 consumers. It required coverage of 300 m$^2$ area for their installation [5]. The power generated being DC had to be converted to AC using inverters and were stored in battery for night supply to the consumers.

Schematic diagram of a solar power plant with its different outfits is shown below in (Figure 3) [6].

These additional outfits (battery and inverter) escalates the cost of PV based power generation still further, cost of which in 2000,

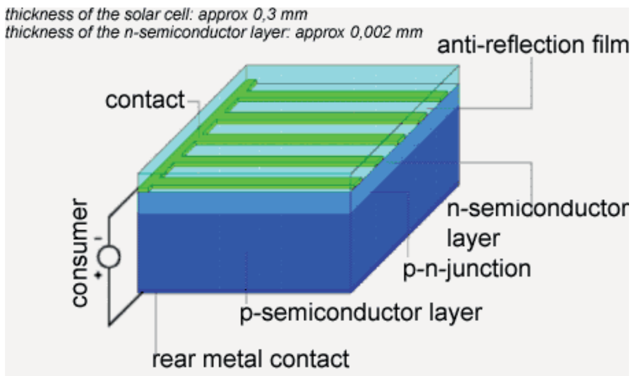


**Figure 1:** Schematic diagram of crystalline Silicon PV cell (Source: Best practice guide - Photovoltaics (PV) [2].

| Type/Material of PV cell | Level of efficiency in Laboratory (%) | Level of efficiency in Production (%) |
|---|---|---|
| Mono crystalline Silicon based | 24 (Approximate ) | 14-17 |
| Polycrystalline Silicon based | 18 (Approximate) | 13-15 |
| Amorphous Silicon based | 13 (Approximate) | 5-7 |

**Table 1:** Efficiency percent of different types of Silicon based PV cells [3].

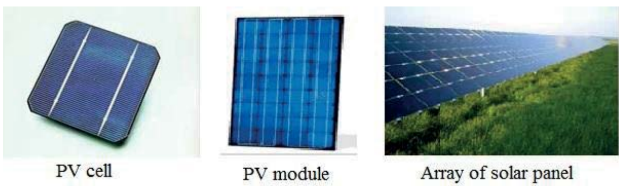


**Figure 2:** A pictorial view of PV cell, module & array of solar panel [4].

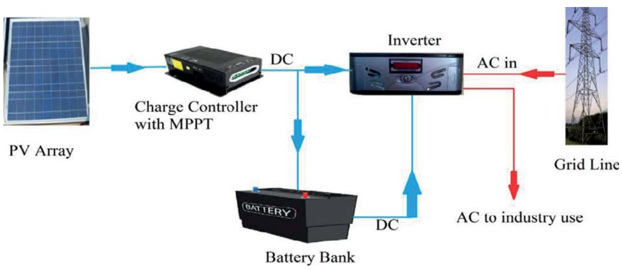


**Figure 3:** Schematic diagram of a solar PV power plant with its outfits [6].

was \$ 4-6/$W_{peak}$ [6]. Such installation though apparently uneconomic, but it helped to improve the economy of that inaccessible place, at Sundarbans, Sagar island, India, from the availability of power supply. They are now being used more widely with Government subsidies in many such inaccessible places.

Such installations subsequently made could be the hybrid system along with other power grid supply line or, only stand-alone type -as per the suitability of installation site. In fact, such hybridization can also be made with wind energy supply, if available.

It may be added that solar PV installation cost has improved a lot since then, and have become much cheaper, not only from the availability of rather cheaper 2nd generation PV cells, but also because of their increased volume of use.

It may be relevant to add that the efficiency of crystalline Silicon PV products ranges from 15-20% with requirement of space 100 sq. ft./kW; whence for thin film PV, average efficiency is 7-15% with space requirement of 200 sq. ft. /kW [4].

PV array site is determined from the availability of space; normally 1 $kW_p$ requiring 8 $m^2$ of roof/space, that faces south with slope of around 30-40° [7]. Since PV functions from the incident solar light, shades of trees etc. would lower the efficiency.

PV systems are fixed to the roof using stainless steel "roof hooks". They robustly get attached to the roof. Fixing these hooks to concrete tiled roof is a rather easier process. But in case they are required to be hooked in slate and clay tiles, adequate measures are needed for their fixing/removal etc., increasing the cost from these extra measure with extra labour cost of the same [7]. In the following figure is shown the mode of fixing solar module over roof surface showing 30° tilt angle, facing the preferred southern side for availing longer hours of sunlight (Figure 4) [4].

## Economic assessment of PV cells

The economic assessment of a PV power plant is mainly decided from the cost of the PV modules required for the concerned plant. Of course, other costs including inverter, battery assembly, labour cost in fixing the modules and installation cost, O and M cost, land cost etc.-are also to be taken into account. The sizing of the inverter, battery assembly, land area requirement etc. are all dependent on the sizing/ number of the PV modules required. The relationship deciding the number of PV modules are hence important, which can be estimated from the following equations that determine the panel generation factor (PGF) and total watt peak rating of the PV modules, as shown below [6].

**Panel generation factor** = Solar irradiance x sunshine hours / Standard test condition irradiance; (where, solar irradiance (kWh/$m^2$), depends on site concerned and sunshine hours, which is normally considered to be 9-10 hours and standard test condition irradiation is considered 1000 kWh/$m^2$) .. [1]

**Total watt peak rating** = Total energy requirement from the PV module (kWh/day) / Panel generation factor (PGF); (where, PGF is determined from eqn. 1 and total energy requirement is case specific, depending on the requirement). [2]

**Number of PV modules required** = Total watt peak rating / PV modules peak rated output; (where, Total watt peak rating is decided from eqn. 2 above and PV modules peak rated output depends on the module type chosen for installation). [3]

It may be relevant to cite a case study as made for a PV plant of 2.5 MW at Jaipur city India. It required 714.1 million INR excluding the land cost, out of which PV module cost was 587.87 million INR [6]; which is more than 82% of the total cost of installation.

Of course, capacity factor of PV plant, which is decided from annual kWh generated for each KW AC peak/8760; is quite decisive in PV economy. In Jaipur case, it showed around 35% [6]. However, it would be case specific and site specific.

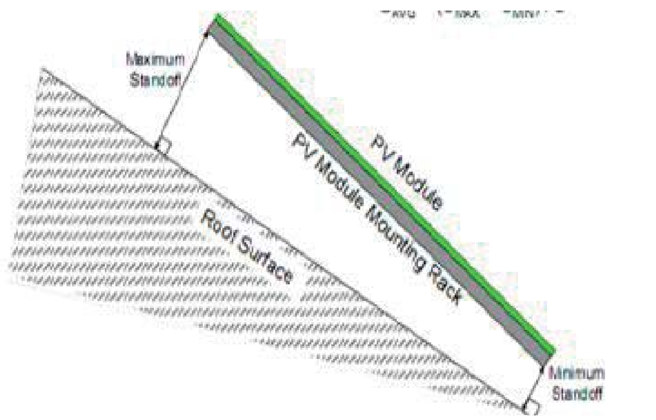


**Figure 4:** PV module fixed over a roof showing the tilt angle facing south for better efficiency [4].

Thereby is determined LCOE (levelised cost of energy), giving the average price the consumer has to pay the investor, for the capital cost, O and M cost etc. incurred with a rate of return which is equal to the discount rate.

In Jaipur case of 2.5 MW PV plant, India, with solar irradiance 617, and capacity factor a little more than 35%, discount rate at 10% and life considered 25 year, LCOE (excluding land cost) showed a value 11.40 INR/kWh, which is = \$ 0.016*11.4 = \$ 0.18/kWh. (1 INR being \$ 0.016 dt 20.8.2015).

## Scope of hybridization

It may be relevant to add that the assembly of batteries may be eliminated if necessary hybridization with Wind energy is made - both the PV and Wind being time specific. The hybridization of one may help the other for 24 x 7 power supply. In addition Hydrogen generation may be tried in for storing electricity during scope of availability of excess supply, through $H_2$/Fuel cell route.

## Utilization of sunlight's heating effect

Different techniques have been improvised to trap the radiant energy of the sun and utilize its heating effect fruitfully both for domestic use as well as in industry -- without taking recourse to conventional energy resources. A few of them briefed below--include Solar Cooker, Solar Pond, and generation of electricity concentrating the heating effect of the sun to derive clean Energy. A brief outline of them are given below.

**Solar-cooker:** A report from IREDA, India, states that an amount of 6.7 million tonne of $CO_2$ emission could be avoided if 3% of Indians switch over to using Solar Cooking [8]. It could be demonstrated building a prototype of cheaper quality solar cooker (life expectancy of 5-6 years ) that 2-3 hours of clear sunshine in tropical country like India, could be enough to cook 2-4 items --- making it a viable proposition. A sample survey made in India, amongst poorer sections of the society, proved that this is cheaper than using conventional fuels used for their cooking [9].

Various types of Solar Cookers are already available in the market - which however needs proper information dissemination, besides R and D on cost reduction (without compromising the quality) for achieving wider acceptability.

**Solar pond:** Solar pond entraps heat energy from sun-light in a novel way. The bottom layer of a water pool is artificially made denser with adequate addition of common salt. Convection current of the heavier bottom layer does not move upwards to shed its heat to the upper layer of the pond and thereafter to the atmosphere as in a normal pond. Thus, heat energy received from sunlight remain stored in the bottom zone. Therefore the heat received from the sun is virtually entrapped in the bottom layer of such ponds, termed Solar Pond.

In Solar Ponds the bottom layer temperature may go up as high as 70-80°C, when the upper surface layer temperature would virtually equalize with the atmospheric temperature Since the salinity gradient increases with depth, the middle layer with salinity/density in between, would have a temperature in between and virtually act as the insulation between the cooler surface layer and the hot bottom layer. This heated water in the bottom layer of the Solar Pond can have industrial use providing heat energy [10].

The Bhuj Solar Pond in India, perhaps one of the largest solar ponds - with dimension of 100 m × 80 m × 3.5 m, required 4000 tonnes of common salt and is functioning successfully supplying heated water required for an adjacent large dairy farm [11].

It is obvious that such solar ponds can only be successful where adequate supply of sea water/cheaper salt supply, and high radiant energy of the sun is assured.

**Electricity generation from solar heating:** It is a power tower, which is a system for trapping solar energy from a large field of mirrors and converting it to heat at high temperature for efficient generation of electricity. All the mirrors track the sun and the heat is focused on a single boiler thermal system. The purpose is to cover the midday load as experienced by utilities. To counter the effect of passing cloud, there is a thermal storage capability filled with oil.

## Merits and demerits of solar energy

Solar Power is rather decentralized by its very nature and the advantage of Solar Energy is that it can supply energy, in inaccessible places as well.

The generation of liquid and solid wastes during wafer slicing, cleaning, processing and assembling of solar PV cells may create health hazards to workers of manufacturing units. This can however be reduced by recycling and from use of suitable traps. Wastes arising from disposal of array of batteries used for solar power stations are also a problem that needs to be addressed. Environmental life cycle assessment made at Utrecht University on multi crystalline solar cells reports emission of pollutants like, fluorine, chlorine, nitrate, iso-propanol, $SO_2$, $CO_2$, silica particles etc. during the production stage of the PV cells as well as from the mining and refining of silica (Utrecht Univ. Report). Module life time has also been suggested in their study as to not exceed 30 years. Recycling of materials in the PV cell manufacture has been advocated in their study for cost reduction.

Solar Energy is by its very nature site and time specific. It has good potential particularly in inaccessible areas, though further R and D studies are in progress for its wider application with economic viability.

## Wind Energy

Wind Energy was in use since long mainly for grinding purposes in wind mills. Generation of Electricity with Wind Turbines, utilizing the aerodynamic lift of the wind, is the recent trend-with global stress upon Renewable Energy Resources. Wind turbines capture the wind's energy with two or three propeller-like blades, which are mounted on a rotor, to generate electricity. The turbines sit atop high towers, taking advantage of the stronger and less turbulent wind at 30 meters or, more above ground.

In fact, the availability of wind is the most important criterion that would determine the deployment of wind turbine in a certain place. By availability it means the wind speed due to which it will rotate the wind turbine so that mechanical energy of the wind is converted into electrical energy through generator. The wind speed decides the efficiency and economy of wind energy application for creating wind farms.

### Theoretical basis of wind energy formation and its scope of use

Wind movement is known to be formed due to the uneven heating of the earth from solar insolation, irregularities of the earth's terrain, and also from the rotation of the earth. The kinetic energy possessed by wind movement can be converted into mechanical energy, which rotates the blade and spin a shaft of the turbine, which produces electricity through generator. The wind turbines are of two types. One of them is horizontal axis wind turbine and the other is vertical axis.

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Horizontal axis based wind turbines are rather more common [12].

Since the power that a wind turbine generates is a function of the cube of the average wind speed of the site concerned; hence small differences in wind speed would cause large differences in productivity and thereby of electricity cost. Also, the swept area of a turbine rotor is a function of the square of the blade length. Hence a modest increase in blade length would enhance energy capture, and thus of the cost component on power generation [13].

Since wind speed is higher at high altitude and also less turbulent, so wind turbines are to be placed at higher hub heights. Thus it becomes important to determine the relationship between the wind speed measured using anemometers at the anemometer measurement height, and the wind speed at high hub height around 25-30 m atop. It is known to maintain a logarithmic relationship between the wind speed at anemometer height (where wind speed is measured) and at the hub height as below [13]:

$V_{h=}ln (H/z)/[ln(A_h/z)/Va]$.. [4]

where, $V_h$ is the wind velocity of hub height at the concerned site, $A_h$ is the anemometer measurement height measuring the wind speed, $V_a$ is velocity of wind at the anemometer measurement height, z is the surface roughness index expressed in length and H is the hub height.

Hub height of wind turbine (at which there is rotor) may vary from 25 m for smaller wind turbines like below 50 kW, to as high as even 100m for large multi - megawatt wind turbines. The surface roughness index varies from 0.008 m to 3 m depending on site characteristics [Surface roughness length for terrain with lawn grass it is 0.008 m, fallow field is 0.03 m, with associated few trees 0.01 m, sites with many trees and few buildings it is 0.25 m, for forest it is 0.5 m, suburbs is 1.5 m, but in city centre with tall buildings it is considered to be 3.0m] [13].

Wind turbines are constructed as per the designated power production capability of the concerned site. It may have three situations, like operating with cut in speed, which is the minimum speed at which the wind turbine can give useable power (3-5 m/s); or, rated speed at which the wind turbine will make designated rated power (8-15 m/s), or the cut out speed at which it will cease to function giving power, like in a cyclone.

A typical diagram showing the relationship of power generation from different wind speed from use of a FL100 brand turbine is shown below in (Figure 5) [13].

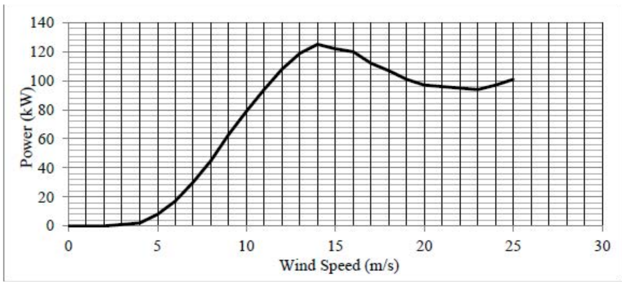


**Figure 5:** Power generation values at different wind speeds from a FL 100 wind turbine in order to calculate the power generation from a wind turbine [13].

It is needed to first determine the wind speed at the concerned hub height of the wind turbine. This is done using logarithmic equation shown above, from measurement of wind speed by the anemometer at the anemometer height. Then to apply it to the turbine power curve as per the above figure to calculate the power output under standard condition of temperature and pressure. Thereafter to multiply with the air density corrections for getting the real condition.

## Power production from wind turbine

Cluster of Wind turbines constituting the wind-farm is an expanding industry. These Wind farms may be stand- alone system or connected with utility power grids. They are fruitfully in operation in many countries - including India (Tamil Nadu, Gujarat) and European countries. It has been reported that global scenario of tapping energy from Wind power increased from 2500MW in 1998 to 10,000 MW in 2003 [8]. The global wind industry now expands at 44 percent year-on-year growth, with a total now (2014) at 369.553 GW. In 2014, the United States represented 17.8% of the world's total installed wind energy capacity, second only to China, which is followed by Germany, Spain, and India [14].

The power generation from a wind farm at a certain average wind speed may be calculated from the following case study made at Malaysia, considering the wind speed at hub height to be 3 m/s and with a turbine of 25 m dia blades, which can be operational in low wind speed as well [15].

The energy per sq.m of an area = Ea = 0.5*air density in kg/m$^{3*}$ wind speed [5].

Thus considering air density to be 1.3 kg/m$^3$, and at wind speed of 3 m/s, Ea =17.55 W [15]. The circular area swept by the turbine of 25m diameter=п*(25/2)$^2$= 491 m$^2$.

Thus, total power grenerated from a single wind mill of above operational data would be = 491*17.55 =8617 W;

which after correcting the efficiency at 50% = 4.309 kW…… [6]

In order to estimate the scope of power generation of a wind farm, covering a particular land area, it is needed to estimate the optimum number of wind mills that can be set up. Too close placement of wind mills will curtail the available wind speed; too far placement would cause uneccesary land pressure. As a rule of thumb, the optimum distance margin between two wind mills is said to be kept around five times the turbine diameter.

Thus per square meter land area the scope of tapping power, from above type of turbine with above wind speed would be=4.309 kW / (5*25)$^2$ = 0.28 W/sq.m land area. ………. [7]

But it is also important to know the capacity factor or load factor of the wind mill, to determine the period when it may be non-functional, from lowering of wind speed below the cut in speed (said to be between 3-5 m/s).The wind speed profile is thus important to know the capacity factor of the concerned wind mill. In Malaysia's context the wind speed profile as determined is shown below in (Figure 6) [15].

It would be obvious that day time wind speed is higher than during night.

But off shore wind speed is higher than on-shore wind speed (of only around 2 m at anemometer height and 3 m at hub height of 30 m, at Malaysia as noted before). Besides off-shore wind is also less turbulent and thus generates more electricity.

In Malaysia, 16 number of such off-shore wind sites could be located, as shown below in (Figure 7). At these sites wind speed reached more than 5 m/s; but during north-west monsoon season only [16].

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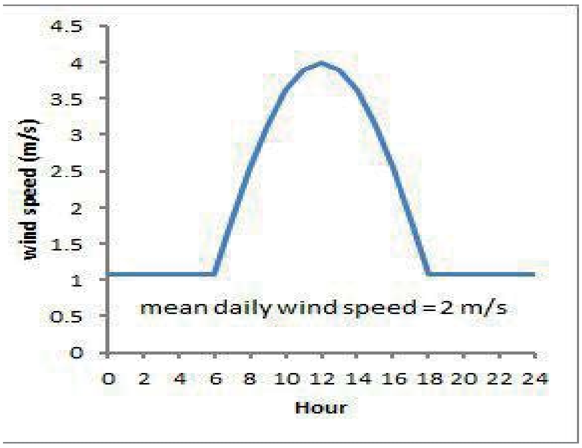


**Figure 6:** Wind speed profile at a typical land site at Malaysia [15].

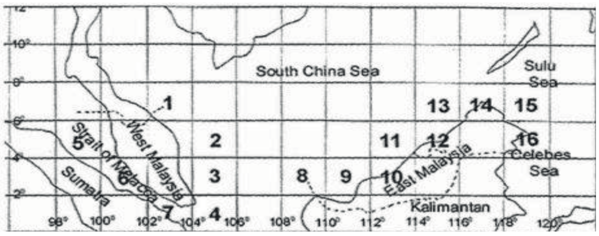


**Figure 7:** Viable wind farm sites of Malaysian coast shown with number marking [16].

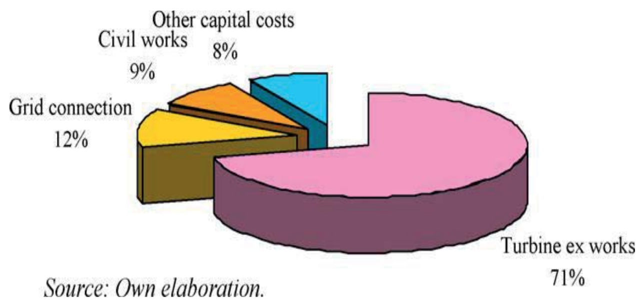


**Figure 8:** Capital cost break up of a land based wind mill [17].

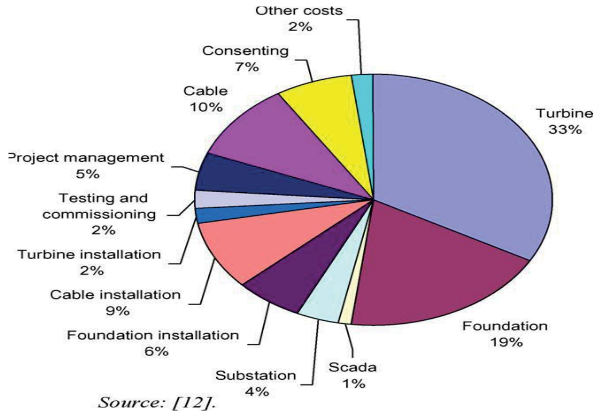


**Figure 9:** Break up of capital cost of an off-shore wind mill [17].

Though normally wind speed at Malaysia is about 2 m/s, which can reach 3 m/s at hub height around 30 m; but at selected sites, particulatrly in south west monsoon it can reach as high as 7-15 m/s [15].

## Economy of wind farm

The cost of the turbine and grid line connecton cost together constitute 80% of the capital cost involvement of a wind mill. Other costs like, construction cost for land – based mills though much less than off-shore wind mills, but is also appreciable. It involves around 10% of the total capital cost. The break up of capital cost involvemengt of a land based wind mill is shown below in (Figure 8) [17].

But in case of off-shore wind mill, the turbine cost together with the foundation cost costitute nrearly 50% of the total capital cost involvenment. Cable cost including foundation of cables involve nearly 20% of the total capital cost. The break up capital cost of an off-shore wind mill is shown below in (Figure 9) [17].

It may be added that though the power generation cost of wind energy is the cheapest amongst all the RE systems, competitive to fossil fuel; but its installation is not cheap. Including all costs, even for a good cut in wind speed site, it involves around $1 million per megawatt (MW) of generating capacity installed [14]. In order to make economically viable, a wind farm should have the minimum power availability of 20 MW or more. Presuming each wind mill having production capability of 750 kW, there should be installation of at least 26 turbines, to generate 20 MW involving $ 20, 000, 000 [14].

Cost of wind energy/kWh is therefore not only dependent on wind speed but also the grid line distance and also whether it is off-shore or, on-shore wind. It had been estimated that with very good wind speed (10 m/sec), it would be around $ 0.04/kWh, whereas $ 0.06-09/kWh for moderate wind speed (6 m/sec) [8].

## Merits and demerits

Life time emission of Carbon equivalent gas is minimum in Wind energy systems; 12 g/kWh (Post note 2004).

Though initial investment needed for wind farm is higher than that of the fossil fuel based power plants, but its life cycle cost requires no extra fuel cost etc. with limited O and M cost only. This makes wind energy an economically viable proposition compatible with fossil fuel power stations at suitable sites, having higher wind velocity for prolonged period.

But its problem is that, it is intermittent depending on wind flow with the cut in speed. Thus stand-alone wind system cannot provide power 24 x 7, round the year. Hence its hybridization with solar PV is stressed upon. Also at times it may create land pressure, if off-shore wind is not harnessed. But off-shore wind though have huge resource availability possibility, is rather costlier from increased grid line availability distance and also foundation cost increase.

In addition it should ensure not to affect species (Eagle etc. birds) and should not block the air traffic route. It is also not encouraged for placement in populated areas from local protests due to noise pollution hazards from it.

# Hydrogen

Hydrogen is considered to be the future energy in the next millennium, being an absolute clean energy. It can be used 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. Hence it has been identified to be the future energy source in the new millennium, for the energy supply and security, climate stewardship with ensured sustainability, particularly in the transport sector [18].

It may be relevant to add in this context that Hydrogen though an environmentally clean fuel, which leaves behind only water on its combustion/liberation of energy, but it is available only in the combined form with water/hydrocarbons, etc. Hence though its resource is almost inexhaustible; but it would always require energy input, either conventional fossil fuels or, renewable energy etc. 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 need not require periodic charging with power to derive power from it.

Hydrogen and Oxygen can be obtained by splitting water in Proton Exchange Membrane Electrolyser (PEME), using in acidic medium [19].

In view of the fact that Hydrogen is a clean fuel for sustainable growth, the Internal Energy Agency (IEA), as early as in 1977 started to promote Hydrogen, with measures to meet the different challenges faced on its production from carbon free sources, as also to sort out its storage problems and explore its scope of use as a clean fuel source [18]. But it has not yet taken off, excepting small scale trials as transport fuel, which still remains in experimental stage only and has not yet picked up commercial viability.

### Economy evaluation

More than 90% of the present day Hydrogen preparation, around 500billion $m^3$/year is produced from steam reforming of fossil fuels (Natural gas, Naphtha, or coal) and only 4% from splitting of water, by electrolysis routes etc. the latter being uneconomic (Isao A. Anon.). Though it can be produced from bio-mass decomposition (gasification and fermentation) and also splitting of water by electrolysis, or by Photo electrochemical/ photo-biological etc routes. The former, bio-mass decomposition is not yet economically viable and the latter is still in the R and D stage [20].

Efforts are now being made to make $H_2$/fuel cell combine vehicles replacing the fossil fuel. Presently attempted alternate energy like, hydrogen/fuel cell route for vehicle movement are: [21]:

- Battery charged vehicle (BEV) using different types of RE systems.
- Fuel cell based electrical vehicles (FCEV).
- Plug-in-hybrid electrical vehicle (PHEV), which combines battery with fuel cell in operating the internal combustion engine (ICE).

But they all are yet to take off [20]. Despite the availability of the technology for availing such vehicles excluding use fossil fuel altogether, lack of facilities like $H_2$ refuelling stations etc. affecting the volume of their use, limit the economic viability of vehicles with $H_2$- fuel cell combine. The scenario may however, change if the social cost (like GHG emission cost and fossil fuel depletion escalating cost) is included, making future Hydrogen economy a viable and better alternative.

It has been said that the cost of production of electricity decides the economy of Hydrogen production by electrolysis, as shown from the figure 10 given below (Figure 10) [22].

In this context it may be added that electricity cost from ocean thermal energy conversion system (OTEC) may be drastically reduced, from the prospect of huge royalty as may be earned from its different by products availed free in course of power production [23]. Particular mention may be made of the improved thermodynamic cycle like Uehara cycle with increased power advantage generation efficiency and with higher by product availability from OTEC (like potable water, sea food, and also mineral water from cold water feed, etc.) [24]. Thus OTEC driven power supply may prove to be economically viable for hydrogen production by electrolysis, when considered such scope of advancement of OTEC technology.

### Merits and demerits

It has been projected by UAE that production of $H_2$ from electrolysis (PEM electrolyte etc.) and thereafter electricity generation through fuel cell, would cost 90% of its electricity production by the turn of the century [25]. As stated before OTEC route of $H_2$ production has the potential to produce cheaper electricity.

But such economic viability of $H_2$ production from OTEC plants are achieved only for larger sized plants, above 50 MW [26]. It has been noted that for use as transport fuel, $H_2$ production of 1500 kg/day is needed in refuelling station feeding 250 cars/day [22]. It can be thereby be estimated that a single 100 MW OTEC plant (net power) producing 2160 MWh/day (running at 90% capacity factor) with production/day of 44, 497 kg $H_2$ by electrolysis, can cater to around 30 such refuelling stations [27], 4.33 kWh is reported to produce 1 $NM^3$ of hydrogen, which is equivalent to 48.5 kWh/kg).

Of course the cost component is required to be improved upon if compared with present day cost of

fossil fuels. This can be achieved from performance improvement and on availing the by-product royalty from OTEC plants, over which it has immense scope.

## Scope of Feasibility Study on Use of Hybrid System (PV, Wind and $H_2$)

Feasibility on scope of application of an energy system would need to identify quantitatively the resource potential of them which mainly decides the economy.

In case of solar PV the

- measurement of solar irradiance at site concerned and
- studies on availability of sunlit hours at site and

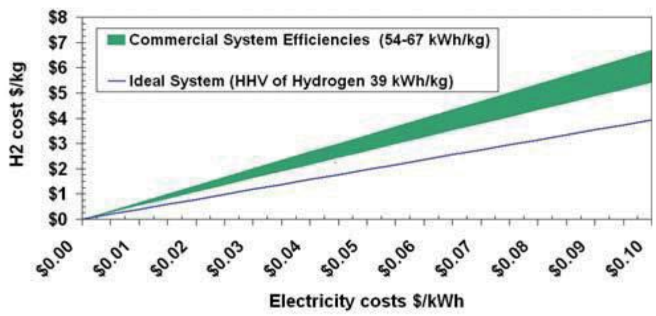


**Figure 10:** Hydrogen production cost by electrolysis with changes in electricity cost [22].

- the scope of area availability for placement

are the three data which are to be availed. They can be availed either from actual site study and/or search from meteorological department data of the concerned zone.

Thereafter based on equation 1, 2 and 3, can be decided number of PV module requirement, which decides the economy, being more than 80% contributing factor of the total cost.

In case of wind energy the

- Measurement of wind speed using anemometer at the concerned site and

- Studies on period/ hours that the cut in wind speed is available at the concerned site and

- Convert the said wind speed at the hub height from the measurement made at anemometer height using logarithmic relationship shown in equation 4 and knowing the terrain data (surface roughness index) and

- Determining the swept area from the diameter of the blades of wind turbine being used.

Thereby can be determined the value electricity availability/sq. m. of the concerned zone using equations 5, 6, 7 -shown before.

It may be added that the turbine cost together with the gridline connecting cost constitute 80% of the total cost of a land based wind farm. In case of off-shore wind farm turbine cost together with gridline cable cost constitute 70% of the total cost plus foundation cost constitute 20% of the total cost.

In case of $H_2$, particularly OTEC-driven $H_2$ production by electrolysis, it is needed to assess:

- scope of temperature differential available between surface warm water (SOW) with deep ocean water (DOW) and

- size of the OTEC plant with net power availability and

- the scope of by products available from the concerned plant, which is an important criterion deciding the economy and

- electrolysis efficiency which varies from a little above 50- 70% (the $H_2$ production estimations as made in the text, as per the data from Nilhous and Vega [27] conforms to 61% efficiency).

- Based on the above data, the cost component of $H_2$ availability may be availed.

In case of $H_2$, it seems further RandD studies are needed on fuel cell technology for $H_2$ production /electricity generation which yet remains an economic challenge.

The combined Hybridization of the above three RE systems are shown in (Figure 11) [28].

The optimized Hybrid model consisting of PV/Wind and $H_2$ system is optimized on sizes of concerned RE systems, using the tool HOMER (Hybrid Optimized Model for Electric Renewable), based on meteorological data and data generation at the concerned site, along with necessary economy evaluation of them [28].

## Exploring Grey Areas of Research

Discussions on RE remained confined to the energy resources like, Solar, Wind and Hydrogen energy and also of their suitable hybridization, depending on the concerned site with scope of resource availability. Besides these conventional RE systems, hitherto unused energy resource that is abundant in our environment, is the low frequency acoustic energy, harvesting of which ensures sustainable development [29]. Such acoustic energy can advantageously be used in the rapidly increasing industries like, electronic devices with low power consumption, such as electronic communication devices, wireless sensor network etc, replacing the electrochemical batteries having limited life span [30].

The acoustic energy may be harnessed to generate electricity on introduction of a quarter wave length straight tube acoustic resonator using a PVDF (poly vinylidene fluoride) piezoelectric transducer. The acoustic pressure gradient causing vibratory motion of the PVDF piezoelectric beams generate electricity due to the direct piezoelectric effect [31]. It may be added that a quarter-wavelength resonator is the preferred choice; showing three times more efficiency than even half wave length resonator with similar diameter and frequency [31]. Using lead zirconate titanate (PZT) piezoelectric cantilever plates it could be noted producing power output of 30 mW from an incident sound pressure level of around 160 db [30]. Of course output power can be increased using multiple piezoelectric plates along a quarter wave length straight resonator tube; a schematic diagram of which is shown below in (Figure 12) [29].

With incident sound energy of 100 db, 4.06 V at 189 Hz could be generated using 5 PZT plates; and 0.37 mW at 190 Hz using 4 plates [29].

It however remains a grey area of research for developing various types of piezoelectric transducers and sound tracking resonators to explore with better harvesting of hitherto unused acoustic energy hugely available in our environment.

## Conclusion

A method could be developed from assessment of the present status of development of solar PV, wind energy and $H_2$ –fuel cell combine, for effective hybridization of these renewable energy systems for availing uninterrupted power supply with better economy and making optimized hybrid model of them.

The parameters needed for resource assessment of wind energy farm installation, by estimating the energy density /sq. m of the site as per the available wind speed; and also of the requirement of PV modules for a given power generation from PV modules, based on solar irradiation at the concerned site – could also be well defined. These

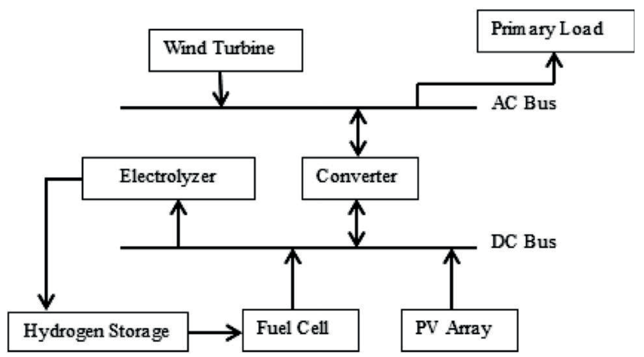


**Figure 11:** Schematic diagram of the hybrid PV/wind/hydrogen system [28].

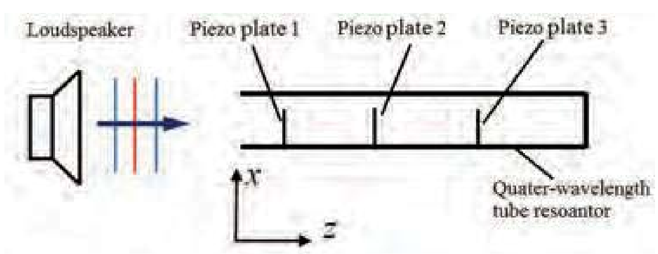


**Figure 12:** A quarter wave length straight resonator (42cm long) with multiple piezoelectric plates [29].

measurements were noted to be important in economy assessment of these two RE systems, Wind/PV combine, where speed of wind at hub height in case of wind energy and number of PV module in case of PV systems, mainly decides their cost effectiveness.

Hydrogen production by electrolysis route, for availing sustainable energy system, though noted to be much costlier than its production through steam reforming of fossil fuels; but OTEC-driven power supply using higher capacity advanced OTEC types, were found to be the solution. The scope of huge royalty earning from different by-products of OTEC makes its electricity production cost cheaper and thus economically viable on availing transport fuel from $H_2$-fuel cell combine.

Making of use of hybrid optimised model for electric renewable (HOMER) tool has been suggested for deciding the extent of application of the RE systems, Solar PV, wind and $H_2$/fuel cell combine, to achieve better economy.

Methodology of data generation at site on determining feasibility for application of HOMER tool, for developing optimised hybrid model of all the three energy systems (PV, wind and $H_2$) could be spelt out.

A grey area of research has been suggested in harvesting low frequency acoustic energy remaining unused, though abundant in the environment. It could be noted that a quarter wave length straight resonator with multiple piezoelectric plates, show better result in electricity production.

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