Solar PV and Wind Powered Green Hydrogen Production Cost for Selected Locations

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Abstract- This paper presents the production cost of green hydrogen using wind-solar hybrid models of hydrogen production via electrolysis. The selected sites are situated in Dhaka, over 100 meters height. Homer Energy software, and the Life Cycle Cost method is used for cost analysis. The lifetime of project is 25 years, with a discount rate of 5%. Annually 4225 kWh of electricity is required for 128520 kg of hydrogen production. The electricity cost ranges between 0.34$ and 5.16$. Four prospective system configurations are found with different production costs. The wind-solar-battery or wind-solar model could become a suitable solution considering available space for installation. For site1, the hydrogen production cost is about 0.08$ for the wind-solar-battery model. The electricity cost is about 0.44$. All configurations are viable for the site2, being the tallest one. The highest production cost is found 0.16$ for Site2. At site2, the production cost is about 0.08$ for wind-solar-battery configuration. The production cost is similar for site3 and site4. Production cost is higher for the Solar and Wind co-generation model. Around 80 turbines are required for solar-wind co-generation. The production cost is around 0.15$. Only two cases are found for only wind-powered hydrogen production, but the higher number of turbines makes this solution difficult to establish. The production cost is around 0.15$ for only wind solutions. The production cost is found comparatively lower than the international market. The model and analysis may contribute to designing, assess and implementing similar projects in Bangladesh to start the green hydrogen economy.

Keywords Green Hydrogen, HOMER Energy, Life Cycle Cost, Solar-Wind, Water Electrolysis.

1. Introduction

Bangladesh government has taken a major investment step toward increasing the Renewable Energy (RE) based power generation in the national energy mix. Among RE resource utilization, solar photovoltaic (PV) technology has the most potential prospect in Bangladesh. Besides this, wind power potential is being explored and expected to be contributing to the RE generation mix along with others like biomass, tidal, etc. There are 41 solar park projects initiated by the government of Bangladesh, having a total of 2175 MWp capacity. Among these, seven are completed and running, eight are in the implementation phase, and 26 are under planning. Besides these, ten wind power generation projects are initiated, having a total of 259.9 MWp capacity. Among these three projects are completed, and in operation, one is being implemented, and the other is in the planning phase. Between these, two installations are off-grid, and the rest are on-gird [1]. These endeavours show a clear interest of the governing body that is trying to maximize the possible RE penetration within 2030.

The conventional hydrogen production method is steam reforming which is not eco-friendly and costs about $0.9 to $3.20 per kg. On the other hand, the Renewable method of hydrogen production is costly due to the investment cost of

RE projects. Study shows that solar PV and wind power production technology costs have become lower than the past decade and are expected to become more affordable within the next ten years. If hydrogen production cost from renewable methods becomes comparatively economical, it will contribute to achieving the decarbonizing planet goal 2050 [2].

Green hydrogen production cost is directly related to the electricity cost. As RE technology price is becoming lower, it is expected that the green hydrogen from RE technology will also be lower within the next decade. As an example, in France, in the year of 2017, the price of solar PV became 50% less than the year of 2011 [3]. Renewable energy sources would fulfil the required energy demand of consumers and benefit economically [4].

Extensive research is being conducted regarding hydrogen production for the last two decades [3]. Research and study show that hydrogen can be produced from solar and wind separately and also from together. It may also be schemed with closed-cycle power generation options as used for energy storage purposes as well as to establish smart grids [5]. Hydrogen production schemes are also being considered as off peak hour energy storage mechanism [6]. A novel energy cycle having a wind turbine, solar PV, alkaline fuel cell (AFC), Stirling engine, and electrolyzer has been studied. The output capacity of that cycle is found to be about 10.5 kW. The electrical efficiency of that system is 56.9%. The electrolyzer consumes 9.9 kW of electricity and produces hydrogen at a rate of 221.3 grams per hour. The Stirling engine consumes 9.85% of energy from the total output, which is supplied from the exhaust heat of the fuel cell. The used wind turbine generates 4.1 kW of electricity in that cycle [7].

Electrolysis is the core part of the green hydrogen production methods. Using Polymer electrolytic membrane (PEM) based electrolysis requires the highest costs cost involvement. In contrast that alkaline electrolyzers are cost-effective. A Levelized cost analysis shows the percentage of electricity cost in the production cost of hydrogen. It is about 30% to 60% of the total cost [8]. The study also states that a 42% efficient 1 kW electrolyzer system produces at a rate of $2.30/kg that is less than the same capacity of PEM-based electrolysis. With the increase of the electrolyzer capacity, the production cost becomes lower. For a 20kW system, it is about $1.90. The study accounts for 15 years' timeline projects having electrolyzer costs of $240/kW; electricity cost $30.00/MWh, yearly inflation rate 2.25%, and interest rate 8% [8].

A location-based study conducted for New Zealand finds the hydrogen production cost, which is about $4.76/kg. The study is about the hydrogen refuelling of heavy vehicles. The project has 20 years of tenure. The Life Cycle Cost (LCC) method is used to estimate the production cost. PEM technology is used with Wind turbines for hydrogen production [9]. The total electrolyzer cost is about $973.89/kW and $52.17/kW for electricity. Here, a 6% discount rate was considered.

Another region-specific study shows that the production cost of green hydrogen would be $2.17 to $1.45 by 2030 in Australia. The electricity cost is about $29.72 to 43.50/MWh, the cost of electrolyzer is about $517.64 to $1450/kW, an interest rate of 8% interest rate, and tenure is 25 years. The analysis indicates that the PV electricity cost would be lesser within 2030. It would play a key role in reducing Green hydrogen production costs [10].

A similar economic assessment is conducted for South Africa, which states the green hydrogen production cost is about 39.55$/kg to 1.4$/kg for several project sites. It counts for 15 different projects in 5 separate locations. The wind is the main RE source there, and water electrolysis is the base technology [11]. This system also uses PEM electrolyzers. The electricity cost is about $0.23/kWh to $2.72/kWh.

Energy storage by hydrogen is also a potential option for a close cycle power production scheme. A preliminary study is conducted for the coastal city Chittagong. It examines a Solar-Wind hybrid model of hydrogen production having a hydrogen storage and fuel cell-based power production facility. It finds the per-unit system cost, which is about $0.09/kWh. The study does not identify or calculate the production cost of hydrogen separately [12].

Another research conducts a comparative regional study for solar-powered hydrogen systems used in the closed-cycle power plants for Russia, India, and Australia. It considers the same power consumption but different solar irradiation conditions to conduct the study to find the capacity of different system components. The study concludes that the system requires a continuous power supply depending on the geography, and hydrogen tank capacity depends on the size of the array. Based on the geographical location, the size of the system auxiliaries would differ from each other, thus differing in production cost [13].

Bangladesh Council of Scientific Research (BCSIR) in Chittagong is establishing a pilot project plant that has a hydrogen refuelling station for Fuel Cell Vehicles (FCVs). It uses biomass to produce hydrogen. The mentioned project is supported by Bangladesh Government [14-15]. However, an electrolysis-based green hydrogen production system is yet to be initiated in the country. The cost of green hydrogen by Solar PV and Wind based systems in Bangladesh may be found less costly due to its geographical location and low-cost electrolyzers developed locally [16].

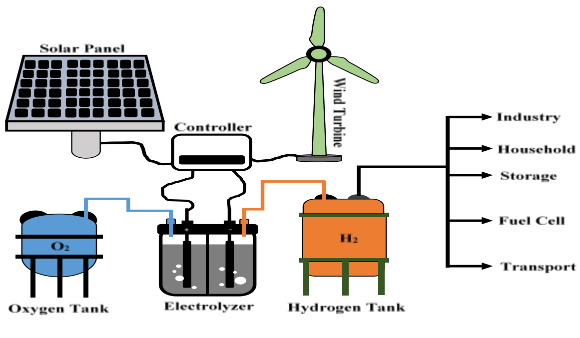


Fig. 1. Green Hydrogen production scheme using Renewable Energy Technologies

So, this research aims to conduct an analysis to determine the Levelized Cost of Hydrogen (LCOH) from Solar PV and Wind for different locations of the country. Figure 1 shows a comprehensive illustration of the green hydrogen production scheme.

2. Materials and Methods

This research selects a major city of Bangladesh which is the most densely populated Dhaka. The city has several high-rise buildings over at least 100 meters in height. Four sites were selected for the analysis. Wind data is measured for one year on a single site among four. Measured data is used to identify the best-suited wind turbines for building rooftop applications [17]. Study shows that 1kW small wind turbines are suitable for power generation on high-rise rooftops in Bangladesh [18].

2.1 Site Information

There are two types of wind data is used for the simulation, measured and retrieved data. Retrieved data is taken from the NASA prediction of worldwide energy resource (POWER) database. The data is composed of 30 year period of time (from January 1984 to December 2013) presented as the monthly average at the height of 50 meters from the earth's surface. Measured data is used to perform the analysis on measured sites over 100 meters of height. The simulation of the rest of the three sites of each location is performed on retrieved data at each building's own height. Table 1 Presents measured data and retrieved data. The measured data are taken from the Dhanmondi site, which is a 23-meter high building. The data is used to simulate the measured site performance for different heights, for this case, 100m, and 150m. In figure 2, the selected site demography is shown with latitude and longitude. Other than the measured site, simulation is performed using the retrieved data.

	(a) Dhanmondi Site	(b) City Centre	(c) Hilton Dhaka	(d) Bangladesh Bank
Height:	23m	171m	152m	137m
Lat:	23.7390497	23.729444	23.793100	23.726600
Long:	90.3830172	90.399452	90.415300	90.423230

Fig. 2. Photographs and location information of selected sites (Image Sources: a: Google Map, b: wikiwand.com, c: bdproperty.com, d: bdproperty.com)

A separate study is performed to evaluate the wind power potential of Dhaka at different heights, comparing the performance of different wind turbines for power production. Data were collected for one year to find out the suitable height and turbine for wind power production projects. The study indicates that over 100-meter hub height is prospective for small wind turbine installations in Dhaka city building rooftops [18].

Table 1. Measured and retrieved wind speed data for Dhaka

Months	Wind Speed (m/s) Dhanmondi (23 m) [Measured Data]	Wind Speed (m/s) Dhaka (50 m) [Retrieved Data]
January	1	3.63
February	1.15	3.63
March	1.75	4.12
April	2.7	5.08
May	2.61	5.29
June	2.99	5.92
July	2.1	6.06
August	2.57	5.37
September	1.71	4.42
October	1.07	3.25
November	0.74	3.07
December	0.85	3.21

Similarly, the solar radiation data is retrieved from the same database. The data period is from July 1983 to June 2005. For Dhaka, the yearly average radiation is 4.59 kWh/m2/day. Figure 2 presents the scaled annual average solar irradiation with the cleanliness index.

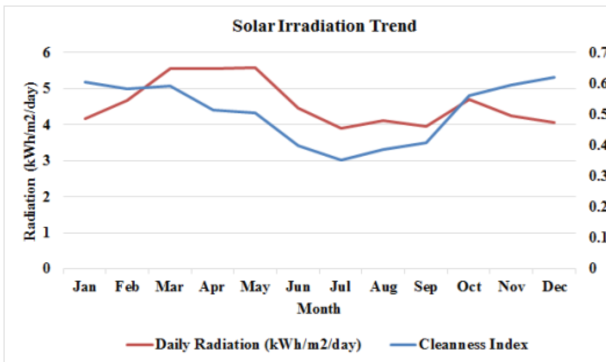


Fig. 3. Solar radiation trend in Dhaka.

The analysis is carried out in three stages. In stage one, all required input and configurations for system components like solar data, wind data, PV module, wind turbine, battery, inverter, electrolyzer, compressor, etc., are set on HOMER Energy software to find out the electricity cost of the designed system. After that, the HOMER optimizer is used to calculate the projected Levelized cost of electricity (LCOE). LCOE is used in stage 3 calculation. In stage 2, all investment costs, fixed and variable operation, and maintenance costs are annualized. The annualized costs are used in stage 3 calculation along with annual hydrogen yield. Stage 3 is the LCC calculation which gives the production cost of the green hydrogen. Figure 2 shows the stage-wise calculation flow and all required inputs for the methods.

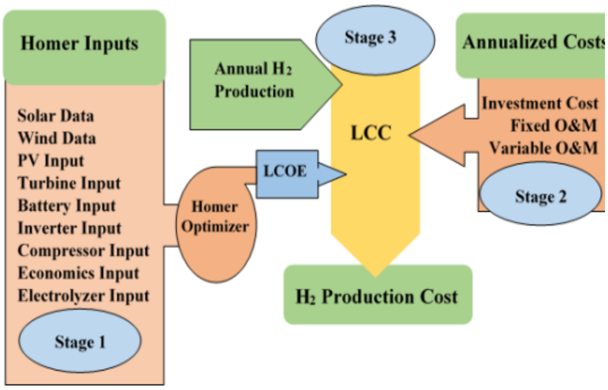


Fig. 4. Stage-wise calculation flow chart.

2.2 Homer Software inputs

The Hybrid Optimization of Multiple Electric Renewables (HOMER), known as HOMER Energy, is a worldwide renowned and accepted tool for optimizing RE-based power production modelling. A large number of technology scope and options with various cost level is available in its library so this tool is also being used to model various types of hybrid renewable energy systems [19]. It incorporates sensitivity analysis options for each system component to decide on the best and worst-case scenarios due to the variation of different system parameters. HOMER produces several economic data based on input like the return of investment (ROI), internal rate of return (IRR), simple payback year, etc. The subjected projects have a maximum lifetime of 25 years. The discount rate is taken as 5% considering the government supports and subsidiaries to the renewable energy projects. Besides this, Bangladeshi Banks have an upper ceiling of a 9% interest rate. The inflation rate of Bangladesh is about 5.48% [20-21].

The requirement of energy is supplied from the RE resources, so the capacity shortage is set as null. In the power generation module of HOMER, PV, wind turbine parameters are set. Wind turbines are set for 10, 15, and 25 years of a lifetime over 100 meters of hub height and according to the buildings' elevation.

As the panel and project lifetime is about 25 years, this gives an advantage of having no replacement cost for the PV modules. The selected PV modules are flat plate monocrystalline types. The specification is as follows. Module Type: Mono-Crystalline Silicon, Model: CS1U-400MS 1500V, Manufacturer: Canadian Solar Inc, Nominal Power: 400 Wp (STC), Voc:53.4 V, Isc: 9.6A, Impp:9.08A, Vmpp:44.1 V, Efficiency: 20.09% (cell) and 19.42% (module),Power Tolerance: 0 ~ +5W, dimension 2078X992X35mm, temperature coefficient -0.36%/ºC, weight 23.4 kg, Front cover 3.2 mm tempered allow, frame Anodized aluminium alloy [22]. The PV module cost is about $0.65/Wp. Per kW capital cost of PV is given as input considering the civil work, wiring, and other miscellaneous costs, so on for wind turbine. The analysis uses a wind turbine developed by Archimedes Green Energy Private Limited. The model is AWM 1500D. It has two blades assembled in a circle, which resembles the shape of a flower. The size or rotor diameter of the turbine is 1.5 m (Width), 1.9 m (Length), 1.75 m (Height), and weighs about 120kg. The operating wind speed of this turbine is 0.9 ms-1, cut-in speed is 3 ms-1, cut-out speed is 14 ms-1, and can withstand up to 50 ms-1. The rated power output is 700 watts, and the maximum is 1000 watts. The turbine is compatible with the maximum power tracking (MPPT) system and has auto and manual braking systems [23]. The wind turbine power curve (including all losses) is presented in figure 5.

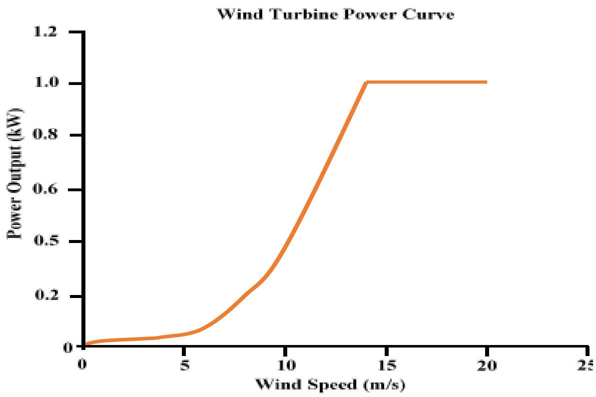


Fig. 5. Wind turbine power curve including all losses

Similarly, the battery capital, maintenance cost, throughput is given in the storage module of HOMER. In table 2, all inputs for the PV module wind turbine and battery are presented. An inverter is used in the design to operate a 2 kW AC (Alternating Current) compressor.

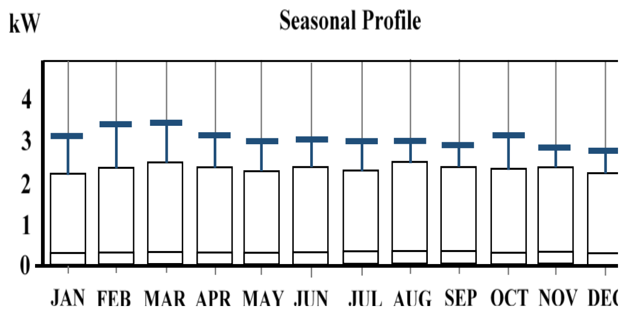


Fig. 6. Load profile of compressor

The load profile per year is presented in figure 6. Each day operating time for the compressor is 3 hours. It starts at 1:00 PM and ends at 3:00 PM. This study uses an alkaline DC electrolyzer. The electrolyzer is locally developed using locally available materials and technologies. The electrolyzer has nine compartments comprising two cells in parallel. The hydrogen production rate of this electrolyzer is 227 mL/min, electrode size is 128 cm^2, and made from stainless steel grade SS316L. It uses Nylon 140 membrane to separate oxygen and hydrogen. The total wattage of the electrolyzer is 3.5 kW. There are 27 units of electrolyzers, each having 127 watts and 42% of efficiency for 0.5M NaOH solution. The price of commercially available PEM electrolyzers is much higher than the developed electrolyzer used for this analysis. Due to the lower efficiency of the developed device, the operating cost would be higher. But for long-run applications like projects, having 25 years life cycle, these low-cost devices would minimize the production cost of per kg hydrogen [24].

Table 2. Energy Side Input cost detail for HOMER configuration

Solar Panel Input Parameter	Per kW Capital ($)	1008.21
	Replacement ($)	1008.21
	Operations and Maintenance per year ($)	23.26
	Life Time (years)	25
	Derating Factor	80
Wind Turbine Input Parameters	Per kW Capital ($)	581.40
	Replacement Cost ($)	581.40
	Operations and Maintenance per year ($)	23.26
	Life Time (years)	10,15,25
Battery Input Parameter	Nominal Voltage(v)	12
	Maximum Capacity (Ah)	83.4
	Round Trip Efficiency (%)	80
	Maximum Charge Current (A)	16.7
	Maximum Discharge Current (A)	24.3
	Lifetime	5 years
	Throughput (kWh)	2016
	Unit Price ($)	145.35
	Maintenance Cost per year ($)	3.49

Initial investment and replacement costs would be considerably lower. Operating costs include electricity, water price which would be the same for both the devices. The only difference is the cost of sodium hydroxide pellets. Sodium hydroxide is available and not a very costly chemical. The electrode of the used electrolyzer is made from 316 grade stainless steel. 316 grade stainless steel is resistant to a wide range of concentration and temperature. It is considered resistant to any molarity solution of NaOH up to 80°C of operating temperature [25]. The operating temperature of the system is around 55°C. Similarly the KOH is non corrosive to this steel grade also [26] but the price of same amount of KOH is more than double to the price of NaOH in local market [27-28]. So, NaOH solution was used to reduce the operating cost. The difference between Initial investment and replacement cost would cover the operating cost for long-run projects. For a 1 kW system, the initial investment would be BDT 1494583 for the imported PEM electrolyzer, whereas the locally developed device would cost nearly BDT 20000. Any replacement of PEM electrolyzers can increase the cost drastically. At present best PEM electrolyzers can run for 40000 hours which is equivalent to 4.5 years [29]. Moreover, Due to the locally developed low-cost electrolyzer, the replacement cost is much lower in comparison to the imported equipment. The project uses locally available PV modules. Currently, Solar panels are available at a much lower price in India and so on in Bangladeshi markets [30]. The used turbine blades and components can also be replaced using locally available resources and materials, which would maintain the projected cost throughout the lifecycle of the project. Figure 7 shows the yearly load profile of the electrolyzer unit. The total electric load is designed to be around 6 kW for this analysis so that the total renewable resource like solar PV and Wind turbines' installed capacity remains around 10 kWp to 12 kWp, which is a common RE installation in Bangladesh at private consumer end. 27 electrolyzers of 127 watts have total of 3.5kW load and a 2 kW compressor leads to a total of 5.5 kW active load for the system.

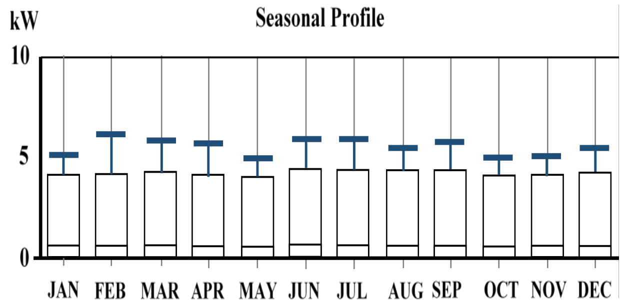


Fig. 7. Load profile of electrolyzer

The plant is designed to operate electrolyzers for 4 hours per day to produce 4.4 kg of hydrogen per hour [16].

Table 3. Load Side Input cost detail for HOMER configuration

Electrolyzer Input Parameter	Capital cost ($)	20406.9
	Lifetime (year)	10
	Wattage	127 w
	Voltage	12.7 v
	Current	10 amp
	Hydrogen production per hour	4.4 kg
	Unit Price ($)	755.81
	Efficiency	42%
Compressor Input Parameter	Efficiency multiplier	0.95
	Capital cost ($)	232.56
	Lifetime(year)	10
	Wattage	2 kW
	Efficiency	95%
	Lifetime	10 years
	Replacement Cost ($)	232.56
	Maintenance cost per year ($)	23.26
Inverter input parameter	Capital ($)	197.67
	Replacement ($)	197.67
	Operation and Maintenance ($)	23.26
	Lifetime (Years)	15
	Efficiency (%)	98

The annual average energy required for electrolyzers is about 14 kWh/day. Inverter, electrolyzer, and compressor configuration data are presented in Table 3. After the configurations are completed, simulation is performed from the simulation panel of HOMER. The simulation returns 634 feasible solutions among a total of 1964 solutions.

2.3 Life Cycle Cost

This research performs calculation of production cost using a well-prepared LCC method. The structure is shown in several methods and published research articles [31-38].

The method mainly takes five cost elements, which are investment cost, variable operation and maintenance (O&M) cost, fixed operation, and maintenance cost, replacement cost. Each cost element is converted into the annualized cost values using the capital recovery factor (CRF).

In Equation 1, the investment cost is given as, Pinv. Water electrolysis cost as Pwe, cost of the compressor as Pc, storage cost as Ps, miscellaneous cost as Pmisc,

$$P_{inv} = P_{we} + P_c + P_s + P_{misc} \quad (1)$$

In Equation 2, CRF is given. In this equation, r is the nominal discount rate, t is the lifetime of the project.

$$CRF = r\,(1 + r)^t / (1 + r)^t - 1 \quad (2)$$

$$P_{inv} = CRF \; X \; P_{inv} \quad (3)$$

There are two categories of operation and maintenance costs. Fixed and variable maintenance and operation cost is presented by equation 4 and equation 5. Annualized costs are presented as y, is denoted for annualized or yearly costs.

$$P_{fom,y} = P_e + P_w + P_{che} \quad (4)$$

In equation 5, Pe stands for annual electricity cost, Pw is the annual water cost, Pche is the annual chemical cost.

$$P_{vom,y} = P_{mc} + P_{bat} + P_{elec} + P_{sal} + P_{rep,y} \quad (5)$$

In equation 6, compressor maintenance cost is presented as Pmc, battery maintenance cost as Pbat, electrical maintenance cost as Pelec, salaries as Psal. The annualized replacement cost is given as Prep, a. Annual replacement cost is included in equation 6. Equation 6 present the annual replacement cost. Here, Prep is the current cost value of a component that is to be replaced. Here, d is the duration at which the annualized cost is calculated.

$$P_{rep,y} = CRF \; X \; (P_{rep} / (1 + r)^t) \quad (6)$$

By combining all these cost elements from the above equations, annualized LCC is formed and presented in equation 7,

$$P_{LCC} = P_{inv,y} + P_{vom,y} + P_{fom,y} \quad (7)$$

The production cost is obtained by dividing the yearly hydrogen production amount in kg by PLCC, a. Annual hydrogen yield is presented as EH2 in equation 8.

$$LCOH = C_{LCC,y} / E_{H2,y} \quad (8)$$

All cost elements of LCC are presented in Table 4. All the costs are annualized using the CRF. The obtained CRF for the project is 0.071. Here, investment costs are composed of major system components required for hydrogen production. The electricity production cost is considered in fixed operation and maintenance cost and obtained from HOMER simulation based on the various case. Annually, about 44480 liters of water are required by the plants. The price of water is about $0.32/liter. The required chemical (NaOH) is about 161 kg having a total cost of $1040.21 kg having a rate of $ 6.43/kg. Similarly, the replacement costs are included in variable operation and maintenance costs.

Table 4. Inputs of cost elements for LCC Calculation Method

Cost Elements	System Components	Cost ($)
Investment Cost (Pinv)	Electrolyzer cost (Pwe)	20511.97
	Compressor cost (Pc)	233.75
	Storage unit (Ps)	2395.98
	Safety and Control Unit cost (Pp)	8181.41
	Miscellaneous costs (Pmisc)	1402.53
Fixed Cost (Pfom,y)	Electricity cost (Pe)	Case-wise input
	Water cost (Pw)	1413.75
	Chemical cost (Pche)	1040.21
Variable Cost (Pvom,y)	Maintenance cost of compressor (Pmc)	23.38
	Maintenance cost of battery (Pbat)	70.13
	Maintenance cost of electrolyzer (Pelec)	220.90
	Salary (Psal)	2571.30
	Annualized replacement cost excluding wind turbine	678.55
	Total Annualized replacement cost (Prep,y)	Varies with turbine lifetime

Replacement cost total varies due to the consideration of several lifetimes of the turbine, such as 10 years, 15 years, and 25 years. For this, various lifetime CRF is also changed due to the duration of use.

Table 5. Annualized replacement cost detail

Items	Replacement Cost ($)	Duration of Usage	Annualized Replacement Cost ($)
Battery	2921.93	5	162.44
Inverter	679.52	15	23.19
Compressor	233.75	10	10.18
Wires, Pipes	818.14	15	27.92
Safety and control unit	8181.41	5	454.83
Sub Total			678.57
Wind Turbine (10 yrs/unit)	584.39	10	25.46
Wind Turbine (15 yrs/unit)	584.39	15	19.94
Wind Turbine (25 yrs/unit)	584.39	25	12.24

Other system components like Battery, Inverter, Compressor, Wires, Pipes, Safety, and control unit replacement cost are obtained considering a single lifetime. Annualized replacement cost detail is presented in table 5.

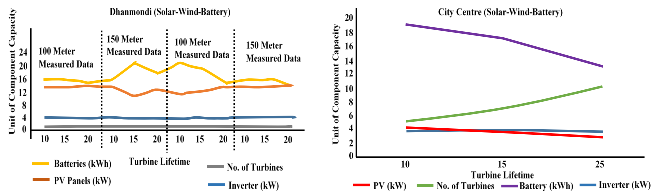
3. Results and Discussion

From the simulation, there are several categories of system configurations obtained. These are only Solar PV-based with battery, only wind with and without battery. Solar PV and Wind without battery, Solar PV and Wind without Battery. In this section, the results summary of HOMER simulation for electricity cost and LCC is presented.

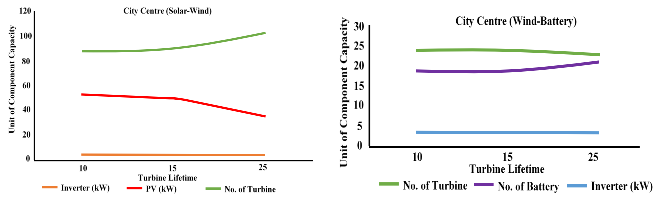
3.1 HOMER Results

As mentioned, there are several categories of system configurations found for the designed solution. Simulation results are found for Solar-Wind-Battery, Solar-Wind, Wind-Battery, and systems having only wind configurations. The input battery is the lead-acid battery; hence using the battery would have some environmental issues. However, there are a number of solutions found which require no batteries at all. On the Dhanmondi site, there is a total of 12 cases found by simulation. System requirements are in one category, which is Solar-Wind-Battery configurations. Figure 8 shows the size of system components according to the hub height and turbine lifetime. All solutions suggest a single turbine for this site for all the hub height and all lifetimes of the turbine. The largest PV module size is 13.97 kW for retrieved data, and 150-meter hub height simulation and lowest is 10.86 kW by measured data on the same height. The maximum number of batteries can be 21, and the lowest is 14 for the same mentioned conditions.

The vertical axis of figures 8 and 9 is the common axis for all units: kW, kWh, and the number of turbines for the given range of unit values. Like battery capacity is expressed as kWh within the given range of the axis value. The axis is named as the unit of component capacity.



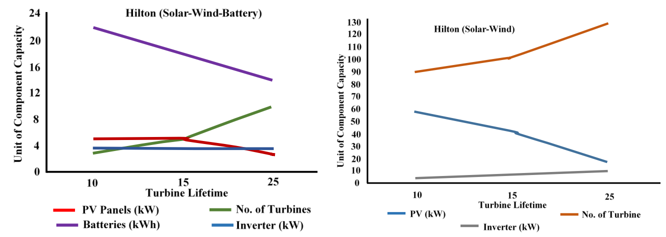
(a)Dhanmondi Configuration (b)City Centre Configuration1



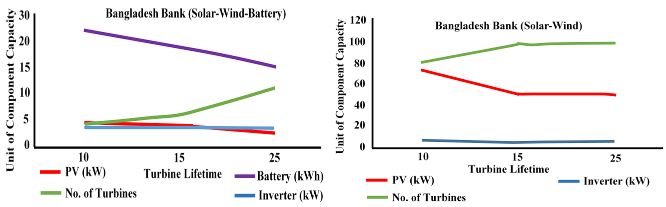
(C)City Centre Configuration2 (d)City Centre Configuration3

Fig. 8. Component size in Dhanmondi and City Centre Site for different configurations

For the City Center site, there are three types of system requirements found among 9 cases. The largest size of PV module is about 53.02 kW for ten years lifetime of 88 wind turbines which is a battery-free system configuration shown in figure b. The highest number of wind turbines is 103 for 25 years project case having a 34.68 kW size of PV module, which is also a Solar-Wind configuration. The lowest number of batteries is 13 among all these 9 cases. Hilton site configurations are shown in figures 8 (a) and 8 (b). On this site, it has been found that only wind turbine installations can support the designed load. However, the number of required turbines is not suitable for rooftop installations. However, this simulation shows the prospect of hydrogen production by using only wind energy.



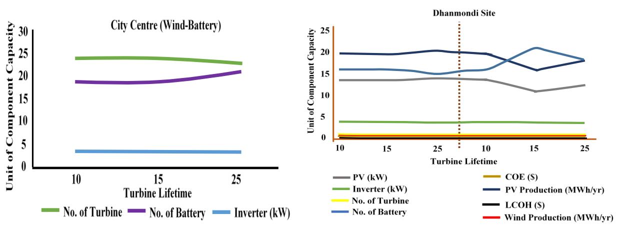
(a)Hilton Site Configuration1 (b) Hilton Site Configuration2



(C) B. Bank Configuration1 (d)B. Bank Configuration2

Fig. 9. Component size in Hilton Site and Bangladesh Bank Site for different configurations

The highest number of wind turbines for Solar-wind-Battery configuration is 10 for 25 years project, and the PV module size is about 2.87 kW requiring 14 batteries. For the Solar wind battery configuration of 25 years project, it was found that 16.14 kW PV module and 129 wind turbines are required. Bangladesh Bank site configuration categories are similar to that of the City Centre site. Three categories of the system are possible for this site. The highest number of turbines for 25 years project is about 99 with the 50 kW PV module size. The case is a Solar-Wind configuration. A similar configuration is found for 15 years project. The highest 22 batteries are required for Solar-Wind-Battery configuration for this site for 10 years project, and 15 batteries with 11 wind turbines and a 2.4 kW PV module is required for 25 year project.



(a)B. Bank Configuration3 (b) LCOE and power production of Dhanmondi

Fig. 10. Configuration of Bangladesh Bank site and Economics of Dhanmondi site

Economics data for all the sites are presented in the following tables. Battery cases are included here, along with other cases of wind-solar and only wind configurations. There is a total of 9 cases found from the simulation performed for the City Centre. Among these, 6 are Solar-Wind hybrid cases, and 3 are wind, shown in table 6. The cost of electricity varies between 0.41 $ to 2.55 $ for any system configuration for City Centre. The highest possible annual electricity generation from PV is about 77.30 MWh, whereas, from wind, it is about 174 MWh, shown in Table 6. Table 6, Table 7, and Table 8 present similar data for other sites. The initial capital cost is presented in 100 thousand numerical figures. Energy production is presented in megawatt hour per annum.

3.2 *Levelized Cost by LCC*

The summation of annualized investment, fixed cost, and variable cost give the annualized life cycle cost (LLC), which is used in equation 8. Variable, fixed cost includes the Levelized cost of electricity obtained from the HOMER simulation for each case. The calculation is performed for each category of cases of all the sites. The annualized hydrogen production is about 128520kg. Dividing the annualized LCC by annual hydrogen production gives the LCOH. The separate results are shown in table 9 and 10. Table 9 presents all wind and solar combined cases, and table 10 shows the results of only wind turbine cases. The production cost of hydrogen varies between 0.08 $ to 0.17 $ for the solar wind hybrid generation model and 0.08 $ to 0.09 $ for only the wind turbine production model.

Table 6. Electricity Cost and estimated power generation for Wind Solar Battery configuration

Site Name	City Center			Hilton			Bangladesh Bank		
Turbine Lifetime (years)	10	15	25	10	15	25	10	15	25
PV (kW)	4.01	3.5	2.79	5.13	5.03	2.87	4.39	3.89	2.36
No. of Turbine	5	7	10	3	5	10	4	6	11
Battery	19	17	13	22	18	14	22	19	15
COE ($)	0.41	0.38	0.36	0.41	0.4	0.37	0.42	0.4	0.38
Initial capital (100 thousand $)	0.14	0.14	0.15	0.14	0.15	0.15	0.14	0.14	0.15
PV Production (MWh/yr)	5.84	5.1	4.07	7.48	7.34	4.19	6.4	5.68	3.44
Wind Production (MWh/yr)	8.45	11.83	16.89	4.59	7.65	15.31	5.59	8.38	15.37

Table 7. Electricity Cost and estimated power generation for Wind Solar configuration

Site Name	City Center			Hilton			Bangladesh Bank		
Turbine Lifetime (years)	10	15	25	10	15	25	10	15	25
PV (kW)	53.02	49.96	34.68	57.44	41.62	16.14	73.68	51.14	50.65
No. of Turbine	88	90	103	89	101	129	81	98	99
COE ($)	2.55	2.13	1.72	2.63	2.19	1.78	2.74	2.27	1.93
Initial capital (100 thousand $)	1.09	1.07	0.99	1.14	1.06	0.97	1.27	1.13	1.13
PV Production (MWh/yr)	77.3	72.8	50.55	83.79	60.72	23.54	107.42	74.56	73.84
Wind Production (MWh/yr)	148.66	152.04	174	136.24	154.61	197.48	113.18	136.93	138.33

Table 8. Electricity Cost and estimated power generation Wind-Battery

Site Name	City Center			Hilton			Bangladesh Bank		
Turbine Lifetime (years)	10	15	25	10	15	25	10	15	25
No. of Turbine	24	24	23	24	24	24	24	25	25
Battery	19	19	21	20	20	20	22	20	20
COE ($)	0.71	0.6	0.52	0.72	0.61	0.52	0.73	0.62	0.53
Initial capital (100 thousand $)	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.22	0.22
Wind Production (MWh/yr)	40.54	40.54	38.85	36.74	36.74	36.74	33.53	34.93	34.93

Table 9. Production cost of hydrogen from Wind and Solar

Site Name	Turbine Lifetime	No. of Turbines	No. of battery	LCC ($)
Dhanmondi (Site1)	10 years	1	16 @ 100 m	0.08
	10 years	1	16 @ 100m	0.08
	15 years	1	16 @ 100 m	0.08
	15 years	1	21 @ 150 m	0.08
	25 years	1	15 @ 100 m	0.08
	25 years	1	18 @ 100 m	0.08
City Center (Site2)	10 years	5	19	0.08
	10 years	88		0.16
	15 years	7	17	0.08
	15 years	90		0.15
	25 years	10	13	0.08
	25 years	103		0.13
Hilton Dhaka (Site3)	10 years	3	22	0.08
	10 years	89		0.15
	15 years	5	18	0.08
	15 years	101		0.15
	25 years	10	14	0.08
	25 years	129		0.13
Bangladesh Bank (Site4)	10 years	4	22	0.08
	10 years	81		0.17
	15 years	6	19	0.08
	15 years	98		0.15
	25 years	11	15	0.08
	25 years	99		0.14

Table 10. Production cost of hydrogen from wind

Site	Turbine Lifetime	No. of Turbines	No. of battery	LCOH (BDT/kg)
City Center (Site2)	10 yrs	24	19	0.09
	15 yrs	24	19	0.09
	25 yrs	23	21	0.08
Hilton Dhaka (Site3)	10 yrs	24	20	0.09
	15 yrs	24	20	0.09
	25 yrs	24	20	0.08
Bangladesh Bank (Site4)	10 yrs	24	22	0.09
	15 yrs	25	20	0.09
	25 yrs	25	20	0.08

4. Conclusion

The analysis shows that there is a total of four system configurations that can be used to produce green hydrogen for these selected locations. For each location and system configuration, the production cost varies. At site1, the production cost is found to be 0.08$ at a rate of COE of about 0.44$. As per analysis, this site is ideal for solar-only installations as the simulation returns only one turbine for each case result. For site2 which has the top height among all the sites, has prospects of all possible configurations like wind-solar-battery, wind-solar, wind-battery. The heights production cost is found 0.16$ for a wind-solar configuration. The most suitable and eligible configuration for this site is the Wind-Solar-Battery configuration. Due to the reduced number of turbines considering the availability of space. For such a case, the production cost is about 0.08$ having a COE of 0.41$. For Wind-Solar-Battery system configuration. For site3 and site4, the production cost is found similar for the same system configurations. For the Solar and Wind co-generation model, the result shows a rise in production cost. Around 80 turbines are required for similar cases in site1 2, and 3. The production cost is around 0.15$. There are only two cases found that use only wind turbine technology that requires no battery. The number of required turbines is significantly high, and the production cost is around 0.15$. However, space might become an issue for the higher number of turbine installations.

In the international market, hydrogen fuel price ranges between US$12.85 to $16 per kg [39]. The most common hydrogen fuel price is about US$13.99/kg [40]. Renewable Hydrogen price in Germany US$3.23/kg, Texas US$3.53/kg [41]. The production cost in a decentralized hydrogen refuelling station in Belgium is about 10.3 €/kg, which uses wind turbines, solar PV, and the national grid as the power source. In Bangladesh, power generation from wind is comparatively challenging at lower heights, but it shows prospects above 120-meter height urban areas. Evident that the government has taken initiatives to establish and develop a handful number of wind power and solar power harnessing plants in different locations in Bangladesh. On the other hand, solar photovoltaic is being extensively used for the last ten years. Now green hydrogen has come into the global interest. Bangladesh can take part in producing it at a lower price and expand to export green hydrogen.

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