DUJASE Vol. 6 (2) 64-71, 2021 (July) https://doi.org/10.3329/dujase.v6i2.59220

Production of Green Hydrogen in Bangladesh and its Levelized Cost

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Received on 27 May 2021, Accepted for publication on 20 September 2021

ABSTRACT

Hydrogen is an excellent source of energy that can be burnt directly and used in fuel cells with no emission to environment. In recent years, green hydrogen has become a research interest in many developed and developing countries. The main barrier to this green fuel is the production cost. Production of hydrogen using solar photovoltaic (PV) powered water electrolysis process might reduce the production cost. This paper presents the determination of the Levelized cost of hydrogen (LCOH) produced from a PV-based electrolysis plant which is built in Energy Institute, Dhaka University. The analysis uses LCOH and Life Cycle Cost (LCC) methods to determine the production cost of hydrogen. HOMER Energy software has been used to determine the electricity cost. The plant's lifetime is assumed to be 25 years, with a discount rate of 5%. The Levelized electricity cost from the invested Solar PV plant is about BDT 37.92, and the pay back period is about four years. The electricity consumption of the hydrogen generating plant is 4225 kWh/year, and the amount of hydrogen yield is 128520 kg/year. It is found that the LCOH of green hydrogen is BDT 3.41/kg by LCOH method and BDT 6.79/kg by LCC. The determined cost is very competitive concerning the international market price which is about US$13.99/kg. If production cost becomes comparatively lower, Bangladesh could become a remarkable green hydrogen producer with a remarkable impact in the international market. The model and analysis might help to design, assess and implement such projects in Bangladesh and establish a green hydrogen economy.

Keywords: Green Hydrogen, HOMER Energy, LCOH, LCC, Solar PV, Water Electrolysis,

1. Introduction

According to the International Energy Agency, global energy demand will increase up to 30% by 2040 [1]. Also, the world has the decarbonising planet goal set for 2050. 2% of global carbon dioxide emission occurs from the production process of hydrogen alone [2]. Non-renewable method of hydrogen production which is mostly the steam methane reformation costs about $0.90 to $3.20. [3]. However the process is not sustainable and environment friendly. The primary task of this research is to produce hydrogen without emitting carbon dioxide, which would be a key factor to achieve global decarbonising goal. Study shows that the green hydrogen production cost will be lower as it is directly related to the renewable energy [RE] production cost and the cost of RE technology is being lowered [4]. Polymer electrolytic membrane (PEM) based electrolysis costs more than the Alkaline based electrolysis for green hydrogen production. Lazard's LCOH Analysis states that about 30% – 60% of the hydrogen production cost taken by the cost of electricity. Hence, the LCOH largely depends on the source of electricity [5]. Lazard and Roland Berger estimates that the 42% efficient, 1kW alkaline electrolyzer system results the LCOH of green hydrogen about $2.30/kg which is lower compared to PEM. Results show that LCOH is about $1.90 for 20kW system of similar efficiency. The estimation is based on the 15 years' timeline with a fixed electrolyzer cost $240/kW, electricity cost $30.00/MWh, annual inflation 2.25%, interest rate of 8%.

An assessment of green hydrogen fuelling for heavy vehicles in New Zealand estimates the LCOH about $4.76/kg. The estimation was based on a project of 20 years lifetime. The Levelized cost of Energy (LCOE) method is used to estimate the cost. The project uses polymer electrolytic membrane (PEM) based electrolyzers and RE resources (mostly wind) for electricity production [6]. For this assessment, considered cost of electrolysis about 973.89 USD/kW and Electricity is 52.17 USD/kW. The considered discount rate is 6%. A study for Australia shows that the possible production cost of green hydrogen would be between 2.17$ to 1.45$ by 2030. The LCOE of renewable energy (RE) from large scale solar PV is between $29.72-43.50/MWh, alkaline electrolyzer cost 517.64-1450/kW, 8% interest rate and 25 years lifetime. The study is based on the LCOE including RE resources and comparing different studies conducted for Australia. It states that the solar PV cost will be considerably lower within 2030 which would be the key factor for the reduction of Green hydrogen cost [7].

An economic viability study of green hydrogen production in South Africa shows that the LCOH ranges between 39.55$/kg to 1.4$/kg. It includes data from 15 sites in 5 different provinces. The renewable energy resource is mainly wind where water electrolysis is the considered method of hydrogen production [8]. The system is based on PEM electrolyzer. The electricity production cost in this study ranges between 0.23$/kWh to 2.72$/kWh.

A study of Hydrogen Energy Storage Based Green Power Plant (Solar-Wind hybrid model) in seashore of Bangladesh shows that per unit cost of the system is 0.09$/kWh. It identifies that the green hydrogen production scheme can be used to store renewable energy for an environmentally safer way. However, the study does not analyse the production cost of hydrogen separately. Beside this the power production model includes a power generator which uses hydrogen as fuel [9].

Bangladesh has developed a hydrogen research centre and a pilot project plant by Bangladesh Council of Scientific Research (BCSIR) in Chittagong. The project includes a hydrogen production plant from bio mass and a refuelling station for fuel cell vehicle (FCV). This project is an endeavour of Bangladesh government to make a sustainable energy mix of the country, which is still largely dependent on gas and coal. The project aims for the research and quality control related to hydrogen production, storage, supply, and infrastructure development [10-11]. However, study and research shows that the Solar PV based green hydrogen production is considered promising and cost effective. The potential of this approach is yet to be explored in Bangladesh. This is a solar boon country. Using solar power to produce green hydrogen might become a prospective business, here. In this paper, the techno-economic analysis of a solar-powered hydrogen production plant is presented along with the LCOH determination.

The objective of this research is to evaluate the LCOH of green hydrogen in Bangladesh using Solar PV technology and locally developed electrolyzer. Within the scope of the study, a hydrogen production plant using solar PV powered water electrolyzers has already been developed by the research group [12]. The site location is the Energy Park of the Institute of Energy in Dhaka University campus. The site has an 11.6 kW PV power plant installed with 3 kW AC load which is a compressor and 3.5 kW load of 27 DC water electrolyzers. The plant produces electricity using photovoltaic solar panels. Electrolyzers uses DC power to produce hydrogen from water electrolysis. Production yield is about 17 kg of hydrogen in a four hour operation period in a single day. The lifetime of the electrolyser is about ten years with minor maintenance [12]. For the maintenance, the downtime of operation has been provisioned in this plan. Within a business year, about 85 days are considered for maintenance and the working day off. It is assumed that the project lifetime is 25 years, and the interest rate is 5%.

2. Methodology

Water electrolysis for hydrogen production is a well-known method. It is considered expensive because of high investment and operational cost. So it is essential to perform an economic assessment of similar systems. This research takes the LCC and LCOH methods as the analytical tool to obtain the production cost of hydrogen. The electricity cost input of LCC is obtained by HOMER ENERGY software considering the existing project design.

2.1 HOMER Energy Software

The Hybrid Optimization of Multiple Electric Renewables (HOMER) is a software developed by HOMER Energy is globally recognized standard tool for optimizing micro grid design in all sectors. It simplifies the assessments of designs for renewable energy (RE) systems. It incorporates a large number of technology options, variation in costs, and energy resources in its library. It uses optimization and sensitivity algorithms to evaluate potential system requirements. It has design tabs where the model data is provided including component cost and resources. The calculate option provides the analysis and simulation of different system configurations, combinations of components, and generates results. It has sensitivity analysis option to find out the impact by the changes in different factors. The software uses a proprietary derivative-free algorithm to obtain the minimal cost which estimates the installation cost, operation cost, maintenance, fuel, and interest over the lifetime of the project. HOMER calculates and finds some economic metrics like return of investment (ROI), internal rate of return (IRR), simple payback year etc. IRR is calculated by HOMER using a comparison between the base case and current system cash flow. Similarly it finds the ROI and simple payback year also.

Figure 1 shows the inputs for HOMER to determine the cost of electricity [13].

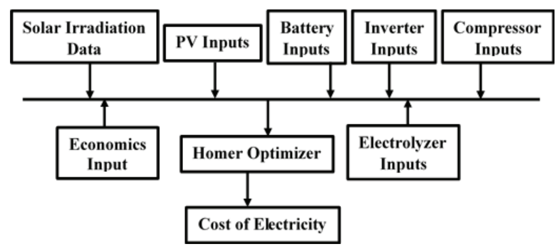

Fig. 1. Input flow of HOMER

2.2 Cost analysis

Cost minimisation is possible by using LCC method in the early stage of the project by identifying the sections precisely. The evaluation of the LCC in terms of cost of per kg hydrogen includes the LCOH method [14-17]. The LCC has several approaches to fit practical scenarios for specific applications. [18-20]. LCC defines the cost elements, the cost structure and relationships between various costs. To use in equation 1, 3 and 6, the discount rate, inflation rate and lifetime of the project are required. The inflation rate published by Bangladesh Bank was 5.48 and the central bank discount rate was 5% in 2019 [21-22]. For the commercial discount rate or loan interest rate, Bangladesh government has declared the upper celling of commercial loans to be maximum 9%[23]. This analysis includes sensitivity analysis also for these two parameters presented in results section where maximum discount rate considered 11%.

2.2.1 Levelized Cost of Hydrogen

LCOH analysis adopts the Levelized cost of energy (LCOE) method. LCOE is a well-known and widely used tool in renewable energy sectors. Here, the numerical value of LCC presents the cost per energy output. Equ.(1) presents the LCOE given by IRENA [24].

$$\text{LCOE} = \frac{\sum_{n=1}^{N}(I_n+M_n+F_n).(1+i)^{-n}}{\sum_{n=1}^{n} E_n.(1+i)^{-n}} \tag{1}$$

Here, N is the lifetime of the project, n denotes for a particular year when a cost occurs, I_n denotes the initial investment, maintenance cost is M_n, fuel cost is F_n, energy generation is E_n in kg and discount rate is i. The presented cost shows the cost per unit of energy or the cost per unit mass of hydrogen [14, 25]. In table 1 all inputs of cost elements for LCOH are given.

Table-1. Inputs of cost elements for LCOH

Cost Elements	System Components	Cost (BDT)
Initial Investment (In)	Solar System	1057816
	Battery	250000
	Safety and Control Unit	700000
	Compressor unit	20000
	Inverter	58140
	Electrolyzer	1755000
	Cylinder	205000
	Pipes	15000
Maintenance Cost (M_n) (For 25 years)	Solar system	50000
	Battery	150000
	Inverter	50000
	Compressor	50000
	Electrolyser	472500
	Water	3024000
	Chemical	2225000
	cylinder maintenance cost	512500
	Pipes Maintenance Cost	375000

2.2.2 LCC Assessment

The adapted LCC structure was taken from the well-developed existing methods and papers [14, 16-17, 25-27]. Figure 2 shows the cost elements flow in LCC method of LCOH determination.

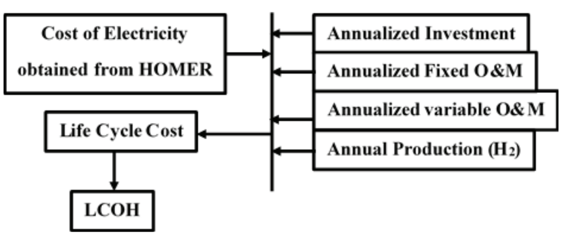

Fig. 2. Cost flow for LCC method

Equation 2 presents investment cost, C_{inv}.

$$C_{inv} = C_{we} + C_c + C_s + C_{misc} \tag{2}$$

Here, C_{we} is the water electrolysis cost, C_c is compressor cost, C_s is the storage unit cost and C_{misc} is the miscellaneous costs. In the LCC method, all costs are annualised by multiplying a factor called capital recovery factor (CRF), shown in equation 3.

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

Here, nominal discount rate presented as i and n is the lifetime of the project.

The annualised investment cost is calculated using the following equation.

$$C_{inv,a} = CRF\ X\ C_{inv} \tag{4}$$

The cost of operation and maintenance (O&M) has fixed cost and variable expenditures.

$C_{vom,a}$ presents annual variable operation and maintenance costs in equation 5.

$$C_{vom,a} = C_{mc} + C_{bat} + C_{elec} + C_{sal} + C_{rep,a} \tag{5}$$

In equation 5, C_{mc} stands for the compressor maintenance cost, C_{bat} is battery maintenance cost, C_{elec} is electrical wiring and related maintenance cost, C_{sal} is the salary expenditure of personnels and annualised replacement cost presented by $C_{rep,a}$. In equation 5, the annual replacement cost is included. The annualised replacement cost is calculated using equation 6. Here, C_{rep} is the present value of a system auxiliary to be replaced.

$$C_{rep,a} = CRF\ X\ \frac{C_{rep}}{(1+i)^t} \tag{6}$$

In the same manner, the fixed operation and maintenance cost (O&M) is represented as,

$$C_{fom,a} = C_e + C_w + C_{che} \tag{7}$$

The annual electricity cost is C_e, C_w stands for the annual water cost, and C_{che} stands for the annual chemical cost.

All the annualised cost is taken into account, and the annualised LCC equation is formed as,

$$C_{LLC,a} = C_{inv,a} + C_{vom,a} + C_{fom,a} \tag{8}$$

After having the $C_{LCC,a}$, the LCOH can be obtained by dividing $C_{LCC,a}$, by the annual yield of hydrogen in kg. Annual hydrogen production is denoted as E_{H2} in equation 9.

$$LCOH = \frac{C_{LCC,a}}{E_{H_2,a}} \tag{9}$$

To perform LCOH analysis, we need to have per unit cost of electricity for this particular case and the yearly production of hydrogen in kg. Table- 2 presents all inputs for LCC.

Table 2. Inputs of cost elements for LCC

Cost Elements	System Components	Cost (BDT)
Investment Cost (Cinv)	Electrolyser cost (Cwe)	1755000
	Compressor cost (Cc)	20000
	Storage unit (Cs)	205000
	Safety and Control Unit cost (Cp)	700000
	Miscellaneous costs (Cmisc)	120000
Fixed Cost (Cfom,a)	Electricity cost (Ce)	160212
	Water cost (Cw)	120960
	Chemical cost (Cche)	89000
Variable Cost (Cvom,a)	Maintenance cost of compressor (Cmc)	2000
	Maintenance cost of battery (Cbat)	6000
	Maintenance cost of electrolyser (Celec)	18900
	Salary (Csal)	220000
	Annualized replacement cost (Crep,a)	58057

2.3 Analysis by HOMER Energy

HOMER uses the latest algorithms to compare complexities to find out the cost-effective system requirements cost of system components are set in the respective module interface [28]. After that simulation is performed from calculation module and results are obtained from results panel. For sensitivity analysis sensitivity parameters are set in each component's sensitivity inputs and simulation results are obtained.

2.3.1 Components and Input Settings

Solar radiation data is shown in figure 3. The HOMER software fetches this data from the NASA Surface meteorology and Solar Energy database. The scaled annual average solar radiation is 4.65 kWh/m2/day for this site.

The project lifetime is assumed to be 25 years. The discount rate for Bangladesh for 2019 is 5%, and the Inflation rate is 5.48% [21-22]. As the total energy requirement would be met by renewable energy, PV, for this case, the annual capacity shortage is considered zero. In the power source module, solar PV parameters are set. Generic Flat-plate PV has been selected. The cost of per kW solar PV is considered including charge controller cost, wires, civil work cost.

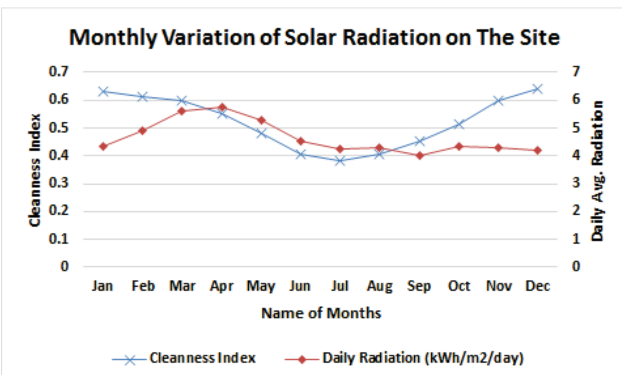

Fig. 3. Monthly Solar Radiation of the site

Twenty-five years have been considered for the lifetime of the panel. So the replacement cost has no impact on the cost analysis and system design. Here, per watt-peak module cost is about BDT 56 BDT [29]. Per kilo-watt cost input of PV module has been given 86706 BDT. Operations and Maintenance cost is 2000 BDT/year [30-31]. The derating factor is 80.

The required number of batteries for the proposed system has been obtained from the HOMER optimizer. The input battery parameters are given as nominal capacity 1 kWh, per unit battery cost is 12500 BDT, Lifetime 5 years, Voltage 12 V, Throughput 2016 kWh and maintenance cost is about 300 BDT per year. The optimized number of batteries is about 20.

The DC power needs to be converted into AC power to operate a 2 kW compressor. The inverter or/converter set in HOMER is 1 kW. HOMER optimises the capacity like the battery. The efficiency of the inverter is 98%, Capital cost 17000/kW, replacement cost 17000 and maintenance cost is about 2000 BDT per year. Lifetime of the inverter is 15 years.

The electrolyser unit which is DC load, produces hydrogen using electricity. The produced gas would be stored by using a compressor. HOMER software requires to configure these load with operating hours. A 3.5 kW capacity electrolyser unit is considered for the system. The unit has 27 electrolysers in it. Each electrolyser is about 127 watt and can produce 4.4 kg hydrogen per hour [12]. The yearly load profile of the electrolyzer is shown in figure 4.

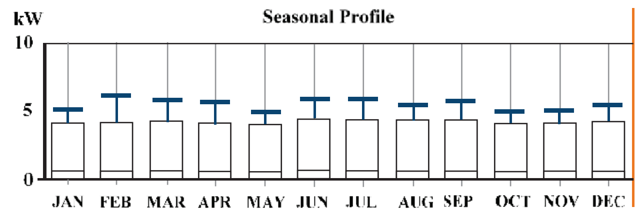

Fig. 4. Yearly load profile of Electrolyzer

Each day it is planned to operate electrolysers for 4 hours. Efficiency of this component is 42% and life time is about 10 years. Per unit electrolyzer price is about BDT 65000. The scaled annual average energy requirement for electrolyser is about 14 kWh/day. A 2 kW compressor has been selected for the project. The compressor is an AC load. The operational hour is set to be 3 hours per day from 1:00 PM to 3:00 PM.

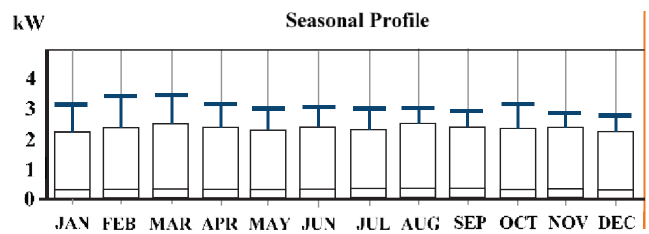

Fig. 5. Yearly Load profile of Compressor

Compressor efficiency is about 95%, and the lifetime is ten years. The scaled annual average energy to be 6 kWh/day. Load profile of the used compressor for a year is shown in figure 5. The cost of the compressor is about 20000 BDT. Per year maintenance is about 2000 BDT.

After setting all parameters, the simulation is processed through the software. The automated calculation returns that about 634 solutions were feasible from 1964 solutions.

This cost of electricity calculated by HOMER is carried forward into the next stages of analysis.

2.4 LCOH Cost Elements and Calculation

In this section LCOH is calculated using equation 1. All required cost inputs are presented with numerical figures in several tables. The component values of equation 1 has been obtained separately.

2.4.1 Initial Investment Cost

The parameter is calculated separately for each system component like Solar PV system, Battery, Compressor, Electrolyser etc. The initial investment of solar PV includes panel cost, power controller, cables, maintenance, and civil works. Table 1 shows the initial investment cost for all necessary system components. The total initial investment cost (I_n) for the total plant is about 4060956 BDT. Figure 6 shows the costs of system components which are related to power generation, storage and control.

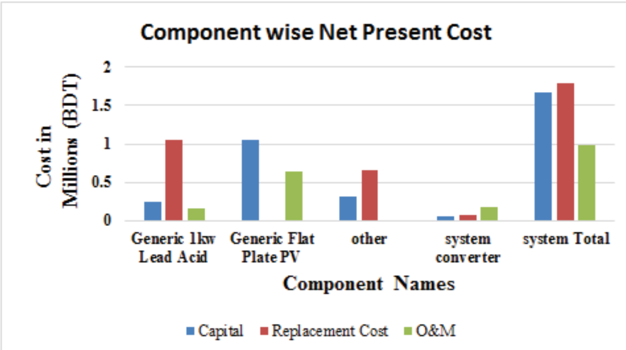

Fig. 6. Cost Summary of power generation Unit

2.4.2 Maintenance Cost

De-mineralised water and chemicals are essential ingredients to produce hydrogen by these electrolysers. The cost of the chemical and water is included. Along with this other maintenance cost is given in the table 1. Each item is expressed as required for 25 years of the project lifetime. The total maintenance cost (M_n) for 25 years is about BDT 6909000.

2.4.3 Energy Generation

The electrolyser can generate about 17 kg of hydrogen in 4 hours of operation per day. Hence, the yearly production of 27 electrolysers becomes 128520 kg and 3213000 kg for 25 years. Data are presented in table 3.

2.5 Cost Calculation by LCC

The life cycle cost method requires all the expenses and investments converted to per annum values. Annualised values are obtained by multiplying a factor called capital recovery factor (CRF), which is given in equation 3. Here, in this analysis, CRF is found to be 0.071.

Table 3: LCOH Cost Elements Summary

(In) The initial investment cost for year n	BDT 4060956
(Mn) Maintenance cost in year n	BDT 6909000
(En) Energy generation in year n	3213000 kg
(i) Discount rate and	5%
(N) Lifetime of project.	25 years

2.5.1 Annualised Investment Cost

The total investment cost includes the cost of electrolyser, compressor, safety unit, storage unit and miscellaneous cost given in the table 2. Here, the annual investment cost is obtained by multiplying the total investment cost with CRF. The total investment cost is BDT 2800000. The annualized investment cost value is found to be BDT 198800.

2.5.2 Annual variable Operation and Maintenance Cost

In the LCC method, operation and maintenance costs are divided. Fixed operation and maintenance costs include mainly the component-wise maintenance costs, replacement costs and salaries. Component-wise variable costs are presented in table 2. Here, the annualised replacement cost ($C_{vom,a}$) is calculated using equation 6. The total annualized variable cost is BDT 304957. This includes annualized replacement cost ($C_{rep,a}$).

Table 4: Annualised replacement cost detail (in BDT)

Items	Replacement Cost	Year of Replacement	Crep,a=CRFX {(Crep)/(1+i)^t}
Battery	250000	5	13898.28
Inverter	58140	15	1984.28
Compressor	20000	10	871.17
Wires, Pipes	70000	15	2389.05
Safety and control unit	700000	5	38915.17
Total			58057.96

The calculation of annualized replacement cost is given in table 4. There are only five components (or items) which are to be replaced over different periods throughout the lifecycle of the system. These are given in table 4 in detail. Each component's annualized replacement-cost is obtained, and the total amount is about BDT 58057.

2.5.3 Annualized Fixed Operation and Maintenance Cost

Fixed cost is identified as the usable commodity required for hydrogen production, which are electricity, water and chemicals shown in table 2. The total annualized fixed cost ($C_{fom,a}$) is about BDT 370172. The simulation shows that the yearly consumption of electricity by the loads is about 4225 kWh. The Levelized Cost of electricity is about BDT 37.92. It gives the yearly cost of electricity is about BDT 160212. The yearly requirement of water is about 44480 litres, and the per litre water price is about 27 BDT. Similarly, 161 kg of chemical (NaOH) is required, which costs about 89000 BDT at a rate kg 550 BDT/kg.

2.5.4 Annualized LCC and Levelized Cost

The summation of annualised investment, fixed cost and variable cost gives the annualised life cycle cost (LLC), which is used in equation 8. The amount is found to be BDT 873930. The annualised hydrogen production is about 128520kg. Table-5 shows the LCC cost totals.

Table 5: LCC Cost Elements Summary

Annualised Investment Cost (Cinv,a)	BDT 198800
Annualized fixed cost (Cfom,a)	BDT 370172
Annualized variable cost (Cvom,a)	BDT 304957
Annual Hydrogen Production	128520 kg

3. Results and Discussion

The optimised electricity production system configuration has been simulated and found to be feasible by HOMER. The recommended system architecture is shown in figure 7. It is found that the system would require 12.2 kW of PV unit, 20 lead-acid batteries, and a converter/inverter of 3.42 kW capacity.

3.1 HOMER Analysis Results

From the table 6, the system's total capital cost is found to be about 1.67 million with the replacement cost of components for 25 years' time period to be 1.79 million BDT.

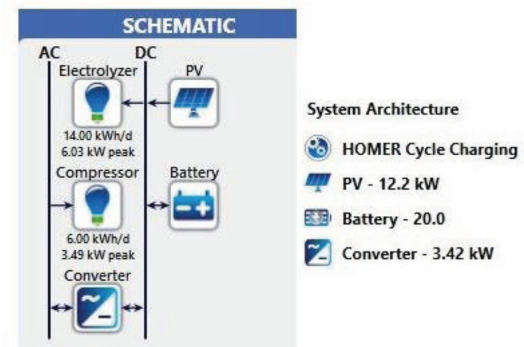

Fig. 7. Schematic of the optimized System Architecture

Table 6: Categorical Cost results (in Lac)

Component	Capital	Replacement Cost	O&M	Salvage	Total
Battery	2.5	10.59	1.59	0	14.68
PV	10.56	0	6.46	0	17.03
other	3.1	6.65	0	1.73	8.00
Inverter	0.58	0.62	1.81	0.21	2.80
Total	16.7	17.85	9.88	1.95	42.5

After the project's lifetime, the total salvage can be incurred is about 195446.85 BDT.

Table 7: Summary Detail of power generation Unit

Economics	Present Worth (BDT)	4.29M
	Annual Worth (BDT)	16198
	Return of investment (%)	41.4
	Internal rate of return (%)	32
	simple payback (year)	4.3
	discounted payback (year)	4.29
Cost	NPC (BDT)	4.25M
	COE (BDT)	37.92
	Operating Cost (BDT)	97109
	Initial Capital (BDT)	1.67M
PV	Capital Cost (BDT)	1056269
	Production (kWh/Year)	18020
Battery	Autonomy (Hour)	24.9
	Annual throughput (kWh/Year)	217
	Operating Hours	0
	Nominal capacity (kWh)	20
	Usable Nominal Capacity (kWh)	12
Converter	Inverter Mean Output (kW)	0.237

The economic aspects of electricity production unit are presented in table 7, the present worth of this power plant is found to be BDT 429909. It's annual worth is BDT/yr 16198. Return of investment is 41.4%, with an internal rate of return having 32%. It has 4.3 years of simple payback and 4.29 years of the discounted payback period. The Levelized Cost of electricity is found to be 37.92 BDT.

3.2 Production Cost of Hydrogen

The Levelized cost of hydrogen is calculated using equation 1 by Considering a 5% discount rate (i) and project lifetime (N), 25 years, along with the other input parameters of the table 4.

3.2.1 Cost of Hydrogen by LCOH

The numerator value is found to be 3.85855×10^{-13}, and the denominator becomes 1.13013×10^{-13}. Here, the $(1+i)^{-n}$ in the numerator is 3.51738×10^{-20}. The LCOH is obtained to be 3.41 BDT/kg (US$ 0.04/kg) of hydrogen.

3.2.2 Cost of Hydrogen by LCC

From the LCC method, dividing the annualised LCC by annual hydrogen production gives the LCOH about 6.79 BDT/kg of hydrogen.

3.3 Comparison of Production Cost Results

Method 1 does not include any replacement cost throughout the lifetime of the project. It has been identified that the battery would be replaced after each five years, similarly the converter would be replaced after 15 years of operation and compressor each 10 years. This yields a replacement cost of about BDT 1090000. Including this cost the LCOH becomes BDT 3.75/kg of hydrogen. The difference between two results is due to the salary, chemical, water and other miscellaneous costs not considered in method 1.

3.3.1 Sensitivity Results and Discussion

Sensitivity analysis is performed based on economic parameters like discount rate, inflation rate and lifetime of the project. It has been observed that the reduced project life increases the production cost. The discount rate has no impact on the results obtained from method 1. Sensitivity results of LCOH is shown in table 8. Similarly the sensitivity analysis is performed for LCC method. The results are shown in table 9. The LCC ranges between BDT 6.79 /kg (US$ 0.08/kg) and BDT 8.79/kg (US$ 0.1). Sensitivity analysis, considering economics parameter shows that the LCOH would range between BDT 3.41/kg (US$ 0.04/kg) to BDT 4.26/kg (US$ 0.05/kg).Other sensitivity parameters like PV derating factor, lifetime, inverter efficiency, battery initial state of charge and throughput are also observed.

Table 8: Sensitivity case results of LCOH method

Discount Rate	Lifetime	LCOH
5	25	3.41
8	25	3.41
11	25	3.41
5	20	3.73
8	20	3.73
11	20	3.73
5	15	4.26
8	15	4.26
11	15	4.26

The cost is found to be within the range of BDT 3.41/kg (US$ 0.04/kg) to BDT 4.26/kg (US$ 0.05/kg) by LCOH and BDT 6.79 /kg (US$ 0.08/kg) and BDT 8.79/kg (US$ 0.1) by LCC.

Table 9: Sensitivity case results of LCC method

Electricity Cost	Discount Rate	Lifetime	LCC of H_2
37.92	5	25	6.79
37.92	8	25	7.28
37.92	11	25	7.83
37.92	5	20	6.99
37.92	8	20	7.46
37.92	11	20	7.98
37.92	5	15	7.34
37.92	8	15	7.79
37.92	11	15	8.27
53.76	5	25	7.31
53.76	8	25	7.80
53.76	11	25	8.35
53.76	5	20	7.51
53.76	8	20	7.98
53.76	11	20	8.50
53.76	5	15	7.86
53.76	8	15	8.31
53.76	11	15	8.79

From this analysis, it is found that the calculated production cost changes due to the economic and system component parameters. The results are not too much deviated even for the highest discount rate and remains below the international price. In the international market, hydrogen fuel price ranges between US$12.85 to $16 per kg [32]. The most common hydrogen fuel price is about US$13.99/kg [33]. Renewable Hydrogen price in Germany US$3.23/kg, Texas US$3.53/kg [34]. The production cost in a decentralised hydrogen refuelling station in Belgium is about 10.3 €/kg(US$ 12.15/kg), which uses wind turbines, solar PV and the national grid as the power source.

4. Conclusion

The outcome of this analysis shows the positive potential of low cost green hydrogen production in Bangladesh. The cost is found lower due to the base production technology which is the electrolyzer, developed locally at a lower cost. Particularly, the PEM technology involves high maintenance and replacement cost over the life time of the project but the shown method requires less maintenance and replacement of major parts of the base technology [12]. PEM technology depends on platinum loading over time due to the impurities impacts the electrodes. Availability of low cost water is also a key factor for the cost of green hydrogen. However, the calculation methods do not includes the cost for land, tax and insurance. It is recommended to add these costs in analysis for similar projects. The by-product of hydrogen production from water is oxygen. The produced oxygen would readily be industrial grade but filtration process may improve the produced oxygen to the medical grade. This may generate revenue from same business model. In Bangladesh, power generation from solar photovoltaic is being extensively used for the last ten years. Now, government is also exploring wind energy in different regions of the country. Wind power can also be incorporated to develop a Solar-Wind hybrid powered hydrogen production model using similar scenario. At present, green hydrogen has come into the global interest. Bangladesh can take part in producing it using its renewable energy resource like solar, wind at a lower price and expand to export green hydrogen in international market. Moreover, the East Asian regional countries and other neighbouring countries like India, China, and Japan are taking actions to establish their own hydrogen economy and assessing demand potential. Study shows that Bangladesh would have a demand of nearly 3 MTOE (million ton of oil equivalent) to 9 MTOE of hydrogen domestically within 2030[35]. So, the green hydrogen production by the presented method may contribute to fulfil the hydrogen demand in Bangladesh also.

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