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Quantitative Analysis of Green H_2 Production Costs: A Comparison between Domestic Developed and Imported Electrolyzers

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Abstract

This study aims to present a quantitative cost analysis of hydrogen utilizing a developed alkaline electrolyzer, a similar-capacity imported alkaline electrolyzer, and a similar-capacity PEM electrolyzer.The research also finds the key parameters that can reduce or increase the production cost. One of the subjected electrolyzers is a locally developed Alkaline Electrolyzer (AE); the other two are similar-capacity imported AE and Polymer Electrolytic Membrane (PEM) electrolyzers. The study uses the Hybrid Optimization of Multiple Energy Resources (HOMER) software for estimating the Levelized Cost of Electricity (LCOE) and the Life Cycle Cost (LCC) method for hydrogen production cost estimation. Results show that the imported electrolyzers have higher production costs due to import duty, fees, and taxes. The estimated cost is 88.4% (AE) and 110.3% (PEM), higher than the locally developed electrolyzer. The economic changes also significantly impact production costs. Government policies can reduce the cost by rescheduling the hydrogen components taxes.

Keywords: quantitative, LCC, hydrogen, comparison, electrolyzers

1. Introduction

Green hydrogen is the most promising fuel for a clean and sustainable environment by 2050. The production cost is a significant barrier to expansion in developing and underdeveloped countries. The target price of green hydrogen by 2031 is $1/kg, set by the US government. The electricity and electrolyzer costs combined contribute more than 80% of the hydrogen production cost. Currently, most of the technologically advanced countries are developing electrolyzers domestically and targeting to lower the price, but it would be tough to lower hydrogen costs in developing countries without domestic development. Imports of such technology to a country would increase the price. Low-cost electrolysis methods and domestic development can benefit any country adopting this cleanest fuel. Since electrolyzers contribute nearly 30% of the green hydrogen production cost, reducing electrolyzer costs would help any country reduce the production cost. Alkaline electrolysis is cheaper and more straightforward than the Ployemer Electrolytic Membrane (PEM) based electrolysis technique. The liquid alkaline electrolyzer technology has matured, and the development process could be convenient, unlike other electrolyzers such as PEM and solid oxide. The raw materials for the liquid alkaline electrolyzer are readily available in developing countries. Thus research must be conducted on developing large-capacity electrolyzers domestically. Besides, an assessment is also needed to compare the cost reduction scope by domestic development rather than import.

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Most green hydrogen researchers are experimenting with PV-based alkaline electrolysis due to its simplicity. A green hydrogen project in New Zealand uses wind power. The production cost obtained by the Life Cycle Cost (LCC) method is $4.76 per kg. The estimation was on a 6% discount rate. Jonathan Yates compares the levelized cost of hydrogen (LCOH) and estimates for a remote plant, investigating different technologies like PV power, optimized electrolyzers, and steam methane reforming (SMR) at Port Hedland, Townsville, Fukushima, Calama, Caceres, and Palm Springs. The study indicates that the size of the plant, electrolyzer efficiency, and capital cost pivot the production cost largely. The study finds that the cost of the subjected plants is between $3.64 and $4.25/kg [1]. However, there is no estimation of the cost reduction scope via domestic development. The cost of green hydrogen production in Australia in the next 10 years will be around $2.15/kg to $1.50/kg. The cost is estimated for Mega-Watt scale solar PV systems, having LCOE between $29.72/MWh to $43.50/MWh, alkaline electrolyzers that cost between $517.64/kW and $1,450/kW, 25-year period, and 8% discount rate. The cost of PV panels is declining and might significantly drop by 2030[2], thus lowering the cost of green hydrogen. The study emphasized cost reduction by reducing electricity costs. However, more information about electrolyzer technology is urgently needed, whether the technology is developed domestically or imported. Green hydrogen production in South Africa is mainly from water electrolysis by wind power. The price ranges between $1.40/kg to $39.55/kg. Polymer electrolytic membrane (PEM) electrolyzers are primarily used. The average electricity cost is between $2.23/kWh and $2.72/kWh [3]. Wind-based green hydrogen production via electrolysis in some off-the-coast islands in Norway exclusively provides the hydrogen for local and community ferry services. The cost is estimated to be $ 6.2 /kg, while it is estimated to be $ 2.8 /kg if produced from grid electricity [4]. Both studies are based on the electricity cost of RE resources rather than the cost of electrolyzer technology. Tonghou has investigated the advantages of PEM electrolyzers. PEM electrolyzers use platinum and other costly and rare metals as catalysts. Despite the higher cost, platinum electrodes and platinum-based catalysts are efficient, among other alternatives [5].

In contrast, Iridium-Oxide and Ruthenium deteriorate quickly due to oxidation. Another study conducted by Saba et al., considering 30 years of data, concludes that hydrogen production by PEM electrolyzers with alkaline battery systems exhibits reduced cost but has a wide price range. PEM-based systems can cost between $306/kW and $4748/kW [6]. These two studies suggest the selection of technology for cost reduction scopes, yet there needs to be more information about implementing the plants, importing the technology, or developing domestically.

This study aims to quantify and compare the production costs by import of electrolyzers and domestic development. Here, the presented literature shows the costs derived from the various projects, electricity sources, and types of electrolyzers. However, research needs to provide more information about the sourcing of the technology and the cost required to transfer or import electrolyzers. Evaluating the possibility of cost reduction through the local development of electrolyzers is necessary. However, materials for developing PEM electrolyzers are not readily available.

An example is a polymer electrolytic membrane and a costly metal, titanium. On the other hand, the raw materials required to develop alkaline electrolyzers are easy to collect, so the alkaline electrolyzers can quickly be developed. This paper compares the production cost of hydrogen utilizing a developed alkaline electrolyzer, a similar-capacity imported alkaline electrolyzer and a similar-capacity PEM electrolyzer. It also identifies the possibility of reducing the cost by any change in policy or special consideration in developing countries like Bangladesh.

The following sections of this paper are prepared sequentially according to the research design. An overview of comparing electrolyzers is given, followed by the method of production cost estimation. The simulation and cost analysis results are presented in the result and discussion section. Then, the key outcomes of the study are given in the conclusions.

2. Overview of the Electrolyzers

This analysis uses three electrolyzers to compare the production cost. One is the outcome of local development, and the others are by imports. The developed electrolyzer is an alkaline type. Therefore, the comparison is with a same-capacity imported alkaline electrolyzer. The study investigates the cost scenario further. It uses an imported PEM electrolyzer to observe the changes in cost for the comparatively costly and advanced technology. Fig. 1 shows a green hydrogen production scheme using solar PV technologies.

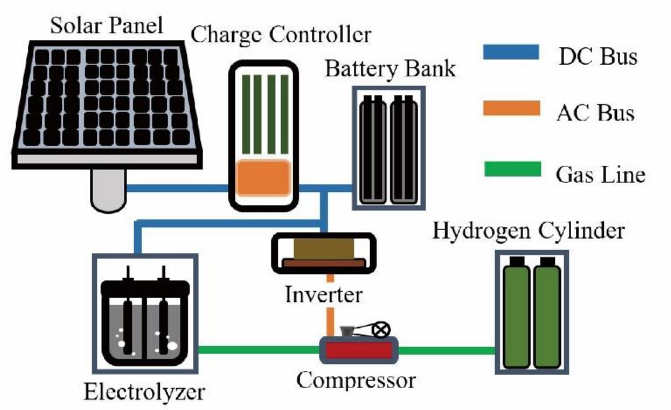


Fig. 1 Simplified Schematic Diagram of the Investigated Solar PV System

2.1 Overview of the Developed Electrolyzer

This study requires the development of an alkaline electrolyzer domestically. Thus, the research developed a liquid-type alkaline electrolyzer using available low-cost materials. After development, a performance study was completed on gas production rate, efficiency, and development cost [7]. The details are given in reference paper 13. The developed electrolyzer has a membrane separator assembly that enables the desired gas separation mechanisms. Oxygen and hydrogen bubbles form on the surfaces of electrodes, which SMA separates. Electrode and SMA together form compartments. There are nine such compartments connected in parallel. Two separate channels are formed by the SMA arrangement so that the gases can pass and not get mixed. The purity of hydrogen by this electrolyzer is 92.5%. The per unit development cost of the electrolyzer is BDT 2500: all the components and raw materials are from local markets. The wattage of the electrolyzer is 120 W DC. Two cells have nine compartments inside the unit. The electrodes' dimension is 128 cm^2, made from stainless steel (316L), and the membrane is using Nylon 140. The gas production rate is 206 mL/min or 0.0123 Nm^3/h. The efficiency of the electrolyzer is 30.62% [7].

2.2 Overview of the Imported Electrolyzer

The imported electrolyzers have similar capacities in terms of production rate. However, the power requirement is slightly different for each. For PEM, it is higher. The physical size and weights nearly match these two electrolyzers. A PEM electrolyzer's price is almost double that of an alkaline electrolyzer.

Table 1 Specifications of the imported electrolyzers.

Characteristics	Alkaline Electrolyzer	PEM Electrolyzer
Model Name	OK-300/500	QL-300
Manufacturer	Hunan Moreshine [8]	Shandong Saikesaisi Hydrogen Energy Co. Ltd [9]
Tag Price	BDT 53500	BDT 108066
Hydrogen purity	99.999%	99.99%
Production rate	272 mL/min or 0.0162 Nm^3/h (STP)	272 mL/min or 0.0162 Nm^3/h (STP)
Electricity Consumption	120w	150w
Dimensions	420x210x365(mm)	420 x 227 x 352 (mm)
weight	13kg	15kg
Environmental conditions	Ambient and dust-free	Ambient and dust-free

The shipment cost is critical for a cost analysis to evaluate an imported electrolyzer. Because the tag price cannot be considered directly in the study as the shipment process incurs an increase in the cost of the good. Table 2 shows the percentage of VAT, tax, and other rates over the price of goods for Bangladesh customs. The package weight of the subjected electrolyzers is 13 kg and 15 kg per unit. For China to Bangladesh flights, a 70 kg package's air shipping cost is around BDT 181500, and additional per kg costs are BDT 2590. The total shipment cost for the alkaline electrolyzer would be around BDT 976450 for a package weighing 377 kg [10]. Custom clearance fees, value-added tax, import or customs duty, and warehouse storage fees are also required. In Bangladesh, the customs clearance fee is 1% of the value of goods [11]. The buying price of 29 electrolyzers will be BDT 1551500. The clearance fee would be BDT 15515. At 15%, value-added tax [12] would be BDT 232725. Customs duty for the final product in Bangladesh is 25% [13]; hence, it would be nearly BDT 387875. Along with the other costs in the table, the total cost for the imported electrolyzers would be BDT 3180065. Similarly, Table 2 presents the breakdown of the expenses for the PEM electrolyzer.

Table 2 Total cost of electrolyzer, including other associated costs

Expenses Related to Import Activity		Alkaline Electrolyzer		PEM Electrolyzer	
Itemized Cost of Imported Goods	Rate	No. of Unit	Total Cost (BDT)	No. of Unit	Total Cost (BDT)
Price of goods	Total Tag Price	29	1551500	20	2161320
Freight cost	Upon Total weight	Total	976450	Total	777200
Clearance Fee	1%	Total	15515	Total	21613
Value added tax	15%	Total	232725	Total	324198
Custom duty	25%	Total	387875	Total	540330
Warehouse storage fee	200 per day	30 days	6000	30 days	6000
Miscellaneous			10000		10000
Total			3180065		3840661

3. Method of Cost Estimation

The analysis uses an optimization software to estimate the cost of electricity, known as Hybrid Optimization of Multiple Electric Renewables (HOMER) and Life Cycle Cost (LCC) methods together to calculate the life cycle cost [14] of hydrogen for each case of the mentioned electrolyzers. The software and the process are well-known and used by the researchers. The HOMER algorithm uses the discounted cash flow (DCF), investment costs, discount rate, and the costs of operations and maintenance. HOMER simulation and LCC calculation are the two methods used one after another to find the life cycle cost of hydrogen. Fig. 2 depicts the flow of calculations and required input parameters. In the first stage, the cost of electricity is obtained for the PV plant by a HOMER software simulation. HOMER needs input component configurations and parameters, as Fig. 2 (Stage-1) indicates. Stage 2 of the calculation uses the obtained COE in the LCC framework.

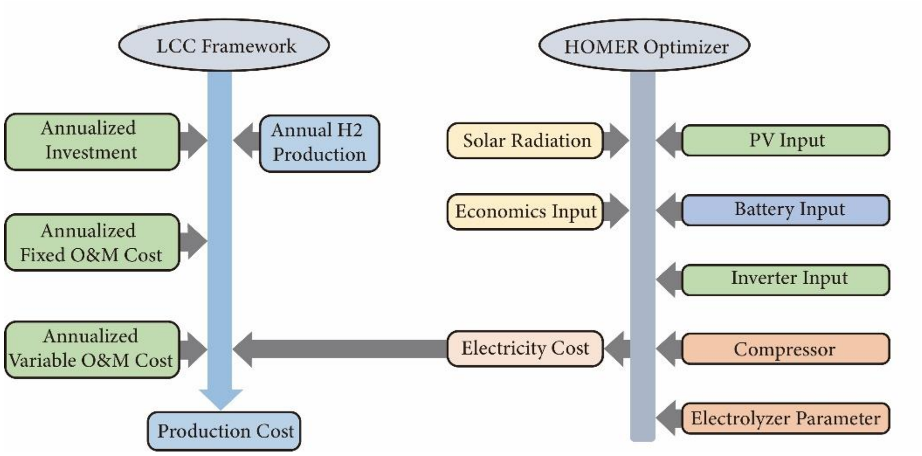


Fig. 2 The stage-wise methodological flow of cost estimation

The study briefly compares each electrolyzer after estimating the hydrogen production costs of these electrolyzers separately. After that, a sensitivity analysis finds the probable impacting parameters that might directly contribute to cost due to their change. Here, the estimation uses two imported electrolyzers. The imported electrolyzers have comparatively lower costs than those in other countries like the USA, France, the UK, and Japan. Since the calculation considers the lower cost of imported electrolyzers among some other countries, the result reflects the maximum leverage in the calculation. Adding two or three more electrolyzers from different countries will result in an increased volume of calculations that would signify the same outcome that the imported electrolyzers would result in a comparatively higher cost than the locally developed electrolyzers.

3.1. HOMER Configuration for COE Evaluation

The HOMER home page is the input area for the project parameters. The discount rate, inflation rate, project lifetime, renewable energy fraction, and annual capacity shortage are to be defined here. HOMER also provides the site location from an interactive map by selection. The input takes renewable resource data from the HOMER resource database based on the area. HOMER hosts data from several organizations like NREL and NASA. For this analysis, the average solar irradiation is 4.65 kWh/m^2/day in the selected location. Fig. 3 gives the daily average solar Global Horizontal Irradiation (GHI) curve. The discount rate is 12%, as instructed by the Bangladesh Govt. [15]. The project lifetime is 25 years.

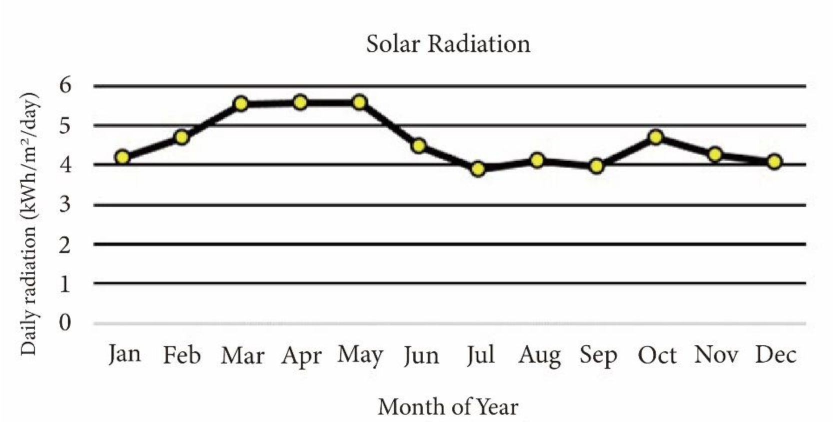


Fig. 3 Global Horizontal Irradiation (GHI) resource input in HOMER

The user must set the models and costs for required equipment like solar PV, inverter, battery, and load on the system design page. Table 3 presents all project parameters of this estimation.

Table 3 List of assumptions for the project

Assumptions	Assumption Value	Reason
Project Lifetime	25 Years	Like most wind and PV projects [16]
Number of Production Off days	85	Holidays and maintenance works
Discount rate	12%	Bangladesh Government Gazette [15]
Solar panel lifetime	25 years	Warranty and lifetime [17]
Battery Lifetime	Five years	Warranty and lifetime [18]
Electrolyzer replacement time	Five years	Expected lifetime [19]
Inverter replacement time	10 Years	Expected lifetime, warranty [20]

HOMER takes inputs such as initial cost, maintenance cost, efficiency, replacement cost, and lifetime for each system component. The input of the costs are in terms of per-unit cost. The HOMER input for per kW PV module cost in the setup wizard considers the total installation cost of the panels. Table 4 presents the itemized costs of each component. The PV panel cost is estimated considering the civil work, frame cost, making cost, wire cost, and misc. The lifetime of the PV module is 25 years; hence, no impact will occur due to replacement. Similarly, the input wizard takes the other components, such as inverters and batteries, into the system.

Table 4 Component-wise investment costs

Cost Items	Component Names	Cost in 25 Years (BDT)	Reference
Investment	Solar System (10.4 kW)	901742	[21]
	Battery (25 kW)	312500	[22]
	Safety gears	5000	[23]
	Compressor unit	15000	[24]
	Inverter (3.49 kW)	59330	[25]
	Developed electrolyzer (3.48 kW)	72500	[7]
	Storage	15000	[26]
	Total	1381072	
Maintenance Cost	Solar system	261000	[27]
	Battery	94000	[22]
	Inverter	87000	[25]
	Compressor	12500	[24]
	Electrolyzer	12500	[7]
	Water	210000	[28]
	Chemical	168570	[29]
	Total	845570	

After configuring all parameters, the simulation runs and estimates the levelized cost of electricity. Then, the LCC framework shown in Fig. 4 takes the COE from HOMER.

3.2. LCC Framework

LCC is a widely used tool for determining the total production cost of a product over its lifetime. As the literature demonstrates, no global solution fits all circumstances, and therefore numerous approaches have been developed, most of which take a relatively general approach. Even though the approaches are distinct, many major processes are comparable to those of the earliest methods. This study takes the LCC framework utilizing similar research works and literature available [30]. The equation for total cost of investments consists of the following elements.

$$T_{inv} = T_{el} + T_c + T_s + T_p + T_m \tag{1}$$

Here, T_{el} is the water electrolyzer cost, T_c is the compressor cost, T_s is the storage unit cost, T_p is the cost for safety gears, and T_m is the miscellaneous cost. LCC analysis requires all simplified terms of the expenses in annualized form. Every single cost can be converted into an annualized cost using the Capital recovery factor (CRF). Equation (2) gives the CRF, and equation (3) performs the cost annualization.

$$CRF = \frac{a(1+a)^m}{a(1+a)^m - 1} \tag{2}$$

Here, a is the interest rate, and m is the project lifetime. Equation (3) calculates the annualized investment.

$$T_{inv,y} = CRF \times T_{inv} \tag{3}$$

The cost for maintenance and plant operation (O&M) is divided into the fixed and variable costs of O&M. $K_{v,y}$'s equation (4) shows annual variable O&M expenditures.

$$T_{v,y} = T_{mc} + T_{em} + T_a + T_{r,y} \tag{4}$$

Here, Tmc is the compressor maintenance cost, Tem is the electrolyzer maintenance cost, Ta is the salary cost and $T_{r,y}$ is the annualized replacement cost. Equation (5) includes annualized replacement costs. Equation (5) calculates the annualized replacement cost. K_r is a system auxiliary's current value.

$$T_{r,y} = CRF \times \frac{T_r}{(1+a)^m} \quad (5)$$

Equation (6) shows the fixed (O&M) cost.

$$T_{f,y} = T_e + T_w \quad (6)$$

T_e is the annual electricity cost, and T_w is the annual cost of water. The annualized LCC equation given as (7) adds the categorical annualized cost components.

$$T_{LCC,y} = T_{inv,y} + T_{v,y} + T_{f,y} \quad (7)$$

After having the $T_{LCC,y}$, the LCOH is obtained by dividing $T_{LCC,y}$, by the yearly hydrogen yield. The annual production is P_{H_2} in equation (8).

$$LCOH = \frac{T_{LCC,y}}{P_{H_2}} \quad (8)$$

The workflow repeats the same calculation process for the three subject electrolyzers to obtain the production cost individually.

A sensitivity analysis prepares observations of changes in costs due to changes in system components, cost of performance parameters, and economic conditions. The analysis also helps identify any crucial situation or parameter that can increase or decrease the production cost.

3.3 Sensitivity Analysis

The system components parameters like PV module lifetime, PV derating factor, throughput (kWh), Initial State of Charge (%), Minimum State of Charge (%), Inverter's Lifetime (years), and Efficiency (%) have a direct impact on the cost of electricity. Hence, the sensitivity analysis selects these parameters. The workflow also investigates the effect of the change by economic parameters like nominal discount rate (%), expected inflation rate (%), and project lifetime (years). The analysis also observes sensitivity by import cost parameters like VAT, tax, and freight costs to determine the impact on import costs.

4. Results and Discussion

HOMER simulation returned an optimized system for the designed load. Fig. 4 shows the HOMER result for the system configuration. The power production system needs a 10.4 kW PV module, 25 batteries, and 3.49 kW inverter. The yearly electricity production is 15388 kWh. Table 5 gives detailed information on the PV power plant. The levelized cost of electricity is BDT 54.64.

The cost of electricity is now available in the LCC framework. The yearly electricity consumption by electrolyzer is about 3897.6 kWh for the developed and Imported AE. The required number of AEs is 29. The PEM electrolyzer needs 3360 kWh of electricity. The yearly electricity cost is about BDT 212964.86 for AEs.

Table 5 Power generation unit cost and performance summary by HOMER

Cost	NPC(BDT)	2.9M
	Cost of Electricity (BDT)	54.64
	Operating Cost (BDT/y)	443768
	Capital Cost(BDT)	1.27M
Solar PV	PV Capital Cost (BDT)	901979
	Electricity Production(kWh/Year)	15388
Battery	Battery Autonomy (Hour)	31.1
	Throughput (kWh/y)	271
	Production Capacity (kWh)	25
	Usable Capacity(kWh)	15
Inverter	Inverter Output (kW)	3.49

The yearly water requirement is about 350 liters, and the per-liter water price is about BDT 24 [28]. Similarly, 15 kg of sodium hydroxide (NaOH) is needed, which costs about BDT 6750. The sodium hydroxide price is 450tk/kg [29]. Fig. 4 shows the optimized system configuration result by HOMER.

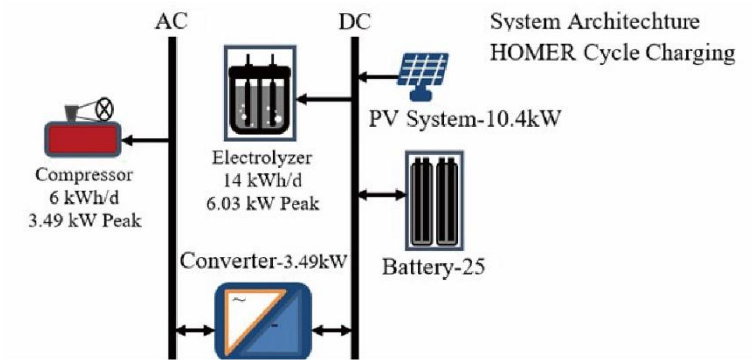


Fig. 4 Optimized system configuration obtained from HOMER simulation

The LCC framework has three major parts of the costs. These are annualized investment cost, annualized variable cost, and annualized fixed cost. Tables 6, 7, and 8 show these costs in order. The sum of annualized investment, fixed, and variable costs gives the LCC by the equation (7). Fig. 4 shows the optimized system configuration result by HOMER.

Table 6 shows the annualized investment details for each electrolyzer. The highest amount for the imported PEM electrolyzer is BDT 504485.93. For imported AE, it is BDT 418608.45. The developed electrolyzer requires the lowest annualized investment cost among the three electrolyzers due to the lower cost needed for the development. Table 7 gives the details and values of the annualized variable cost. Table 7 includes the variable parameter of salary that incorporates the labor cost. However, the labor cost may vary between countries and is onerous to consider in a standardized format. However, the labor cost is comparatively lower in underdeveloped countries than the developed nations. The paper emphasizes the impact of import activity on green hydrogen production costs. The other parameter for any plant is the labor cost parameter, which will add the amount to the final estimated cost and result in the same difference against each type of electrolyzer.

Table 6 Annualized investment cost for three electrolyzers

Cost Items	Developed AE	Imported AE	Imported PEM
(Tel) Electrolyzer cost	72500	3180065	3840661
(Tc) compressor cost	15000	15000	15000
(Ts) storage unit	15000	15000	15000
(Tp) Safety Gears	5000	5000	5000
(Tm) miscellaneous costs	5000	5000	5000
Total	112500	3220065	3880661
Annualized	14625	418608.45	504485.93

Table 7 Annualized variable cost detail for three electrolyzers

Cost Items	Developed AE	Imported AE	Imported PEM
(Tmc) maintenance cost for the compressor	500	500	500
(Tem) the maintenance cost of the electrolyzer	500	500	500
(Ta) Salary	96000	96000	96000
(Tr, a) annualized replacement cost.	2929.64	106783.63	158245.43
Total	99929.64	203783.63	255245.43

Table 8 Annualized replacement cost detail for all three electrolyzers

Component Names	Cost of Replacement (BDT)	Time for Replacement (year)	Replacement Cost (BDT)
Compressor	15000	10	615.77
Wires, Pipes	1500	15	34.94
Safety Gears	2000	5	144.69
Storage	15000	5	1085.20
Developed Electrolyzer	14500	5	1049.03
Imported Alkaline Electrolyzer	1450000	5	104903.02
Imported PEM Electrolyzer	2161320	5	156364.82
Total for Developed Electrolyzer			2929.64
Total for Imported Alkaline Electrolyzer			106783.63
Total for Imported PEM Electrolyzer			158245.42

The variable costs for all the electrolyzers are the same except for the replacement costs. The PEM electrolyzer requires catalyst loadings or electrode replacements every five years. However, it also depends on operation conditions and water quality, which may result in a quicker replacement. In this analysis, the best performance scenario is considered.

Similarly, the imported and developed AE need replacement over five years. The PEM electrolyzers do not require chemical costs. Table 8 provides the replacement cost data.

The replacement cost calculation requires the CRF, the capital recovery factor obtained using equation (2). The CRF is 0.13 for this project configuration.

Table 9 presents the details of the annual fixed cost. The electricity consumption by the developed AE and imported AE is the same, and the cost of electricity is the same. The annual water consumption is the same for all three electrolyzers. The chemical cost for imported AE is higher due to the higher cost of KOH than NaOH. The developed electrolyzer uses NaOH as the electrolyte, but the imported AE needs KOH for H_2 production. The PEM requires lower electricity costs due to its lower consumption of electricity. The fixed cost for the PEM electrolyzer is the lowest among all the three electrolyzers. Table 9 presents the details of the annual fixed cost of three electrolyzers.

Table 9 Annual fixed cost detail for three electrolyzers

Cost Items	Developed Electrolyzer	Imported AE	Imported PEM
(Te) annual electricity cost	212964.86	212964.86	183590.4
(Tw) annual water cost	8400	8400	8400
(Tche) annual chemical cost	6750	8750	0
Total	228114.86	230114.86	191990.4

Table 10 gives the cost comparison summary with other performance parameters. The developed AE unit can produce 1579.9 liters or 141.09 grams of hydrogen in 4 hours of daily operation. Hence, the yearly production becomes 401452.8 liters or 401.45 m^3 or 35849.74 grams or 398.56 Nm^3. [1000 L = 1 m^3], [1-liter H_2 = 0.0893 gram in STP condition].

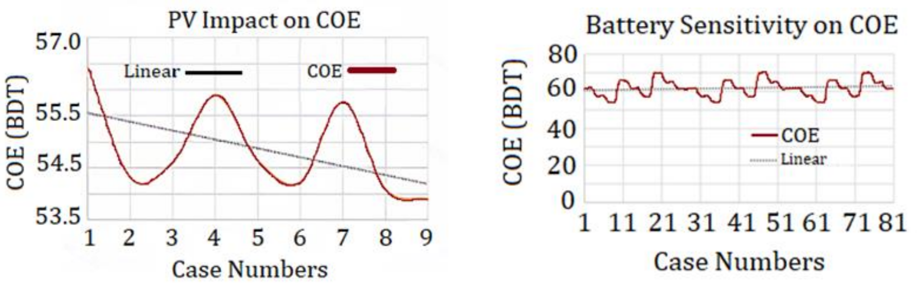
The yearly hydrogen production yield for the imported AE and PEM is about 47335.57 grams or 526.19 Nm^3, considering the per unit production rate to be 272 mL/min (STP) for the same operating condition.

The lowest LCC for the developed AE is BDT 342669.5, and the highest is for PEM, i.e., BDT 20103.96. The imported AE results are BDT 852506.94. Production cost is BDT 9.56/g for developed AE, BDT 18.01/g from imported AE, and BDT 20.10/g for imported PEM.

Table 10 Summary of comparison between developed and imported electrolyzer

Parameters of Comparison	Developed AE	Imported AE	Imported PEM
Yearly Energy Consumption	3897.60 kWh	3897.60 kWh	3360 kWh
Yearly Hydrogen Production	35.85 kg	47.34 kg	47.34 kg
Wattage per unit	120 W	120 W	150 W
Production Rate	206 mL/min or 0.0123 Nm^3/h	272 mL/min or 0.0162 Nm^3/h	272 mL/min or 0.0162 Nm^3/h
Energy Required for per kg H_2	108.72 kWh/kg	82.33 kWh/kg	70.98 kWh/kg
LCC	BDT 342669.51	BDT 852506.94	BDT 951721.75
Production Cost (BDT/kg)	9558.49 BDT/kg	18008.17 BDT/kg	20103.96 BDT/kg
Production Cost (BDT/g)	9.56 BDT/g	18.01 BDT/g	20.10 BDT/g

The graphs in Fig. 5 and Fig. 6 show the sensitivity analysis summary for system components and economic conditions. PV module sensitivity is obtained for a lifetime and derating factor. Fig. 5(a) shows the sensitivity impact of PV parameters, and 5(b) shows the battery sensitivity on coe. The values vary between 70 and 80 for the derating factor and 15 and 25 years for the lifetime.



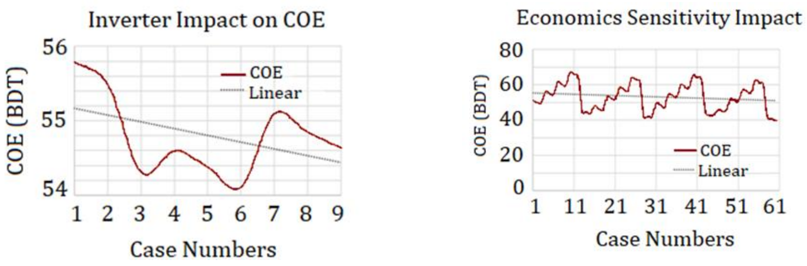
(a) PV parameter impact on COE (b) Battery sensitivity impact on COE

Fig. 5 PV and Battery sensitivity results for COE variations

The coe varies between BDT 53.89 and BDT 56.44. The x-axis of the graphs shows the cases simulated for the sensitivity conditions, and the y-axis gives the cost of electricity corresponding to the case number. For example, in Fig. 6(a), case number 1 returns the coe about BDT 56.5, and case number 9 returns BDT 53.89. All other graphs present the summarized data in the same way. There are four sensitivity parameters for the battery to take into account. Taking minimum State of charge (80% to 100%), maximum state of charge (40% to 60%), lifetime (3 to 5 years), and throughput (1210 kWh to 2016 kWh) result in the coe to be varied between BDT 54.42 to BDT 65.93. Fig. 6(b) shows the variation across the cases.

Fig. 6(a) shows the sensitivity impact for the inverter. Inverter efficiency varies between 95% and 98%, and lifetime is between 10 and 15 years. The cost ranges between BDT 54.11 and BDT 55.79. Graph 6(b) shows the impact of economic sensitivity. Variations of expected inflation (5.48% to 6.5%), discount rate (5% to 12%), and project lifetime (15 years to 25 years) result in the coe varying between BDT 49.76 to BDT 67.24.

Since the production cost of green hydrogen depends on the electricity cost, it is evident that the higher electricity cost or energy price will cause the hydrogen price to get inflated. In the presented sensitivity analysis, the overall change in energy price, in this case, electricity produced from a PV plant, varies between BDT 49.76 and BDT 67.24. In that case, the results of the hydrogen production cost vary between BDT 9.03/g and BDT 10.93/g.



(a) Inverter sensitivity impact on COE (b) Economics parameter impact on COE

Fig. 6 Inverter and Economics sensitivity results for COE variations

The component replacement cost is also a key parameter of sensitivity. Here, the estimated cost of each electrolyzer replacement time is five years. The sensitivity analysis takes 3 to 7 years for all the electrolyzers. Table 11 below gives the estimated production cost of the analysis. It says that if all other conditions remain the same, the two years of increased lifetime would reduce the production cost by 3.2%. On the other hand, if the lifetime gets reduced by two years, an increment of 4.2% is observed. The cost of maintenance and salaries are also incrementally contributing parameters to production costs.

Table 11 Summary of comparison for replacement sensitivity

Lifetime (Replacement time)	Developed AE	Imported AE	Imported PEM
Three years	9.57 BDT/g	18.57 BDT/g	20.95 BDT/g
Five years	9.56 BDT/g	18.01 BDT/g	20.10 BDT/g
Seven years	9.55 BDT/g	17.56 BDT/g	19.44 BDT/g

The sensitivity of component replacement costs can impact the production cost. The efficiency of PEM electrolyzers is superior to the locally developed alkaline electrolyzers. The replacement cost of the main components of the PEM electrolyzers incurs higher costs throughout the project life. The ratio of the yield and replacement cost impacts the production cost incrementally. For PEM, The catalysts get loaded on electrodes on an average of 4 years of runtime. The manufacturers themselves perform platinum catalyst loading. The logistical complexities would impose substantial delays with the higher production cost. The process of this activity may hamper production for months. Besides, maintaining the quality of demineralized water is the most critical task for ensuring the longer life of the PEM electrolyzer. Fouling occurs in electrodes due to water impurities, which is another problem. However, imported alkaline electrolyzers would require lesser replacement costs than PEM, yet they would be higher than the locally developed electrolyzers using locally available materials.

4.1 Supply Chain and Logistical Challenges

The supply chain of the imported electrolyzer involves collecting raw materials, processing the materials, making the sub-components, and then producing the final product as a total electrolysis system that also includes recovery of reusable material or precious metals at the end of product life. A report from the Office of Energy Efficiency & Renewable Energy (EERE) indicates that the Proton Exchange Membrane Electrolysis Cell (PEMEC) and Solid Oxide Electrolysis Cell (SOEC) are not commercially available yet and do not have any established manufacturing supply chain. The drawbacks in the supply chain indicate that importing would pose several risks to continuing longer projects and the environmental aspects of disposing of or recycling. There are several component manufacturers and system providers in the global market. However, more insight and detailed information are needed to be made publicly available. Some fuel-cell manufacturing companies provide or produce some of the components of the electrolyzers. Since the global demand for this technology is low, the supply chain must still be established to support the robust and stable manufacturing industry. Due to these missing links in the supply chain, green hydrogen production technology, i.e., electrolyzer technology, should be developed locally so that long-term projects can avoid unwanted delays due to technical issues and component replacements. In connection to this, the USA, some countries in Europe, and some countries in Asia have the potential to develop domestic capacity for developing electrolyzers to avoid the risks of long-term projects.

4.2 Future outlook on the issue

The efficiency of PEM electrolyzers lies between 60% and 80%. However, Alkaline electrolyzers have lower efficiency, between 50% and 70%. The PEM electrolyzers can produce comparatively higher purity (99.95%) hydrogen than alkaline (99.9%). However, cost is a crucial concern for the PEM. The water quality is a must to maintain the PEM electrolyzer's expected lifetime, which gives advantages to the alkaline electrolyzers. Development is going on for both technologies, such as the development of new methods of platinum loading by mixing with other less expensive metals to form low-cost alloys where the amount of platinum will be less. Besides, experiments on zero-gap alkaline electrolyzers are going on to increase efficiency. Currently, there is little information about the possibility of reducing electrolysis costs from the PEM electrolyzer's point of view. The cost is lower due to the reduction in the price of the photovoltaic panel. This reduction means that electricity is gradually getting cheaper since the PV price is becoming low. However, cost reduction may happen if the green hydrogen production scheme or plants become widespread and have robust supply chain management. Since the electrolyzer supply chain has yet to gain stability, and more public information is unavailable, Technology transfer and international collaboration will help local researchers or developers to increase the efficiency of the locally developed electrolyzers. If a single country could manufacture electrolyzers and all components, making all its materials available in the local market, green hydrogen would likely become popular in solar-abundant countries. It would then also establish a secure supply chain. However, it would be hard for PEM to meet these conditions due to the unavailability of platinum and high-end products like polymer electrolytic membranes. So, alkaline may become a better choice for popularizing the green hydrogen production scheme in underdeveloped and developing countries, at least for the initial periods.

Popularizing green hydrogen production using locally developed electrolyzers or imports would have several environmental impacts during its life cycle since it uses solar PV systems; the disposal and recycling of the PV modules after the project need to raise concerns. Additionally, the periodical maintenance of electrolyzers will create opportunities or challenges to handle scrap components like stainless steel electrodes, connecting pipes, spacers, PVC sheets, plastics, wires, and chemicals. Chemicals can be reused or recycled within the project. After the project, the residual chemicals can be processed and reused in the textile, die, or cleaning industry. The locally developed electrolyzers would be disassembled and can easily be recycled since there are no precious metals or materials. A specialized process of recycling and metal recovery is needed for PV modules or PEM. If the green hydrogen scheme gets popularized, the recycling industry will also have a chance to emerge within the countries.

Reducing the cost of green hydrogen production depends mainly on electricity and electrolyzers. Since PV prices are getting low, green hydrogen costs are being reduced. The technology for electrolyzers is needed to localize. Besides, some countries are trying to make and change policies to support green hydrogen and setting targets to lower the price within a period or landmark. India has targeted reducing the cost of green hydrogen to $1/kg by 2030. The country is to adopt a circular economy to support the project. But India currently has a linear economy.

Australia is targeting to drop production prices by 37% in 2030. They have precisely set their goals to become Asia's third major hydrogen exporter and establish a record for hydrogen safety, domestic job opportunities, and worldwide certification mechanism mechanisms. They are using PV and wind turbines mainly for hydrogen production. Robust policy and investment from the Australian Renewable Energy Agency (ARENA) giving grants to large-scale hydrogen production projects. The USA exploits PEM and Alkaline electrolyzers with steam methane reforming (SMR) and carbon capture and storage (CCS) to produce green hydrogen. They had set a goal to reduce the green hydrogen price to 1$/kg within 2031. However, they need some help in achieving the target. Reports indicated that the USA needs to invest more in new research projects to achieve the goal. They had provided subsidies to the green hydrogen projects to reduce the cost. Reducing green hydrogen production costs is a holistic approach. It would require policy and technology upgrades and scaling up the capacity of both hydrogen-producing plants and electrolyzer manufacturing. An important issue is that most underdeveloped countries are still subsidizing fossil fuels. If fossil fuels get continuous subsidies, clean technologies like PV, wind, and hydrogen would never be profitable like fossil fuels. If the government, authorities, and international bodies make policies to subsidize clean technology and stop subsidies on fossil fuels, clean technologies might become more available at lower cost. A holistic approach suggests several initiatives to reduce the cost of green hydrogen. It includes scaling up the hydrogen production plant from 1MW to 20MW, Automating electrolyzer stack production on a gigawatt scale, expanding industrial PV-based hydrogen production to increase capacity-based efficiency improvement, and growing international targets to reduce the price of hydrogen.

A single country may only be able to resolve some of the issues. The technically advanced country in a region could play an important role in including all its neighboring countries in making a consortium to raise awareness and share technologies to promote the local development of electrolyzers and other components. A robust regional supply chain will reduce operational and maintenance time. Hence, international collaboration is a key to expanding green hydrogen. India may play a vital role in increasing the usage or production of green hydrogen in the South Asian region. Bangladesh and India have partnerships in the food and energy sectors. If they particularly tie upon the joint venture of electrolyzer development, both countries would benefit in the green hydrogen sector. In addition, If there is a hydrogen hub in the SAARC countries, each country may establish hydrogen infrastructure and the supply chain jointly. If it happens, the operational and technological support will be available in a shorter period. The regional policies and memorandum of understanding will be important to reduce import costs from a sister country. Regional consortiums and international platforms may be vital in establishing a far-reaching hydrogen economy.

5. Conclusions

The study analyzes and quantifies the differences in green hydrogen production costs. It contrasts domestically developed electrolyzers, especially a liquid alkaline type, with similar capacity imported liquid alkaline and PEM electrolyzers—a part of this study was accomplished previously, where a liquid alkaline electrolyzer was developed. A simulation tool, HOMER, calculates the LCOE and LCC frameworks to estimate hydrogen production costs for all the subject electrolyzers. The study conducts a sensitivity analysis to see the impact of electricity and how it contributes to production costs.

(1) By assessing all the obtained results, it is observed that the imported electrolyzers have a cost difference of 88.4% (AEs) to 110.3% (PEM) from the locally developed electrolyzers.

(2) The study identifies the typical costs involved in importing an electrolyzer. It finds that the estimated expenses significantly differ due to freight, tax, and duty for the imported electrolyzers. Minimizing these two items contributes to reducing the cost of imported electrolyzers and thus can reduce production costs.

(3) As sensitivity analysis shows, the production cost largely depends on the project lifetime and discount rate. It suggests that economic parameters like inflation will also increase import costs since they have a direct relationship with foreign currency valuation.

(4) The results of this work investigate the difference between production costs on projects considering the imported electrolyzers and locally developed electrolyzers. The locally made electrolyzers can reduce the cost of green hydrogen. The promotion of this concept may lead to international collaboration. It may also create a regional consortium to expand the bilateral relationship, awareness, and exchange of technologies between neighboring countries. Since the supply chain of electrolyzers has yet to achieve a robust and dependable form, international collaboration to develop electrolyzers locally will lead to a promising attempt to reduce the cost of green hydrogen production.

This study concludes on two aspects of initiatives to reduce hydrogen production costs in developing countries. The first one may result in uniform technological development regarding alkaline electrolyzer technology in all the developing countries. Knowledge transfer, technology transfer, and local, private, government, or foreign research investments may accelerate alkaline electrolyzers' local development activities. It could create a new market for electrolyzers and help evolve or create scope for local manufacturers to be involved in making different capacity alkaline electrolyzers or components.

The second one is the change or development of a new policy; a separate green hydrogen policy is essential for developing countries. Subsidies for green hydrogen equipment imports, such as fees, duties, and taxes, may be removed or minimized, enabling investors to establish green hydrogen production plants using state-of-the-art electrolyzers. However, electrolyzer suppliers must ensure after-sales support services at a minimal cost for developing countries.

All these endeavors may contribute mainly to reducing green hydrogen production costs in underdeveloped countries with abundant solar irradiation resources.

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Conflicts of Interest

The authors declare no conflict of interest.

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