

Green Hydrogen Production Using Water Electrolysis Powered by Hybrid Solar Wind Energy – Cost Benefit Analysis

N. Ntombela*, S Mamphweli, S. Rathilal, E.K. Tetteh

Abstract—Energy demand, along with rapid industrialization and population growth, poses threats to the depletion of natural resources and ultimately energy insecurity. Additionally, the extensive use of fossil fuels leads to the release of greenhouse gases (GHGs) such as carbon dioxide (CO₂), sulfur oxides (SO_x), and nitrogen oxides (NO_x) into the atmosphere. South Africa, one of the world's major contributors to carbon emissions, seeks green energy as an alternative to its coal-based energy economy. Herein, the production of green hydrogen, with great potential and benefits as an energy carrier, comes at a cost. This study explored the techno-economic analysis of producing green hydrogen via Proton-Exchange Membrane Electrolysis powered by a hybrid solar-wind system. HOMER-PRO software was used to simulate the green hydrogen plant configuration. The levelized cost of hydrogen (LCOH) for the production of green hydrogen was 16.98\$/kgH₂ to 24.998\$/kgH₂ and LCOH of the transported hydrogen ranged from 8.94\$/kgH₂ to 17.88\$/kgH₂. The capital costs and operational costs that were simulated to build up and maintain the renewable energy system, water electrolysis system and green hydrogen storage were \$8,350,000 and \$383,365 per year respectively. The evaluated configuration, comprising 600 kW wind turbines, a 700 kW photovoltaic system, a 600-kW electrolyser, a converter, a 434 kW/100 kWh Li-ion battery, and a 400 kg sized hydrogen storage tank proved to be both capital and operationally feasible. This demonstrates a strong potential for sustainable green hydrogen production and storage by leveraging renewable energy sources to reduce fossil fuel dependency and emissions. Future work should focus on optimizing system performance under variable conditions, integrating smart grid capabilities, assessing environmental impacts, and exploring scalability for industrial deployment.

Keywords—Carbon Dioxide Emissions, Electrolyser, Green Hydrogen, Renewable Energy.

I. INTRODUCTION

The release of excessive amounts of greenhouse gases (GHGs), has become a pressing global issue that demands immediate attention. This has led to climate change and global warming, a crisis that is still being tackled. The primary culprit is the use of fossil fuels as the main energy source, leading to the release of GHGs such as carbon dioxide (CO₂), methane (CH₄), sulfur oxides (SO_x), and nitrous oxide (N₂O). The increased atmospheric concentration of GHGs has led to global warming, driving climate change. Among GHGs, CO₂ accounts

for 75% of total emissions, and its emissions have increased by more than 100% over the previous four decades. [1]. The rapid expansion of industrialization, coupled with globalization, is a significant contributor to the release of pollutants into the atmosphere. This global issue is further exacerbated by the excessive use of fossil fuels in various sectors and processes. [2]. Various sectors including power industry, transport, agriculture, industrial process, and fuel exploitation. South Africa is one of the major contributors to CO₂ emissions, ranking at 14th place globally. It accounts for 42.8% of total emissions. This is due to burning fossil fuels and being heavily dependent on them as a source of energy. The continued use of fossil fuels not only increases GHG emissions but also depletes them. This concern has threatened energy security not only for the present generation but also for the next. [3].

Green hydrogen (GH) is attracting increasing research interest due to its potential to play a pivotal role in a low-carbon economy, from production to use. GH, produced via water electrolysis powered by renewable energy sources such as solar and wind, aligns with the Sustainable Development Goals (SDGs) 7 (Affordable and Clean Energy) and 13 (Climate Action). GH can serve as a primary energy storage medium and is particularly significant in the transportation sector, where it can be used as fuel for cars, trucks, aviation, and ships. However, the high cost associated with producing, storing, and transporting GH has been a significant barrier to the full-scale implementation of GH technology [4].

II. PRODUCTION OF HYDROGEN

Hydrogen can be utilized via various technologies, such as the production of methane and ammonia, metallurgy, oil refining, and electronics [5]. Hydrogen technology is beneficial; however, like any other technology, it has its disadvantages. The benefits of hydrogen are that it is renewable, a clean source of energy, non-toxic and highly efficient. The disadvantages are that it is financially straining to produce, depending on the technology used to produce hydrogen, there could be carbon emissions, and it isn't easy to store. Therefore, it is crucial to focus on producing green hydrogen on a large scale for commercialization, with 95% of the hydrogen produced via water electrolysis. [6]. There are four different types of electrolyzers that can be used to produce green hydrogen. These electrolyzers are Proton Exchange Membrane (PEM), Alkaline Water

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Electrolyser (AWE), Anion Exchange Membrane (AEM) and Solid Oxide Electrolyser (SOE). Energy from the renewable resources is converted into electrical energy that is used to power the production of green hydrogen. Therefore, the hydrogen power supply is a key factor for the production process of hydrogen to achieve [7].

III. STORAGE AND TRANSPORTATION

Various storage options can be explored for GH. These options are high-pressure hydrogen tanks, metal hydride storage, adsorbent storage and chemical storage, Fig. 1 [8]. Thus, when evaluating the type of storage to use, various factors, such as costs, environmental impacts, efficiency, and suitability, should be considered. The type of storage used influences the type of transportation selected for GH [8]. Large-scale GH storage helps minimize inconsistencies between GH supply and demand, especially in the export supply chain. For hydrogen to be an energy source in the future, it depends on how hydrogen is stored, and its characteristics make storage complicated and expensive [9].

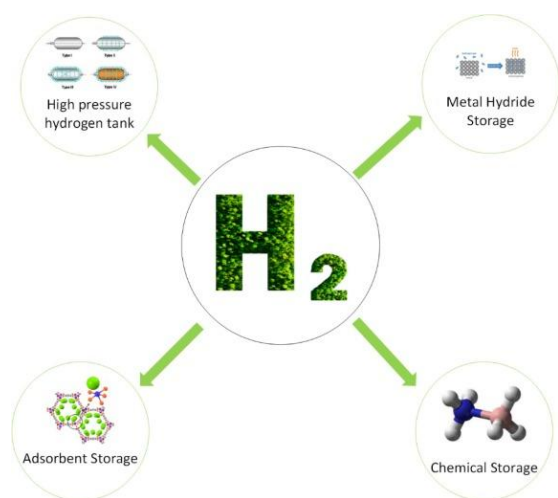


Fig. 1 Various types of green hydrogen storage [8].

GH can be transported via various modes, such as gaseous tube trailers or cryogenic liquid trucks, on roadways, rail lines, pipelines, and barges. The cost of storage and transportation of GH over long distances poses a hindrance to international trade and the widespread acceptance of GH. Conducting a techno-economic analysis will confirm the viability and determine which storage or transportation option will be more practical and cost-efficient, and provide grounds for optimization of various options [10].

IV. ECONOMIC ANALYSIS

Pinpointing the precise expenses related to the electrolyser is proven challenging. This can be based on various factors such as the ambiguous boundaries for estimating costs. This can lead to inaccurate comparisons across the various electrolyser technologies. However, comparisons of costs and evaluating expenses is still possible [11]. The costs of green hydrogen, various cost factors, including capital expenditure (CAPEX) and operating expenditure (OPEX), were evaluated, and the associated costs and effects on the levelized costs of hydrogen

(LCOH). CAPEX includes capital investments for the electrolyser system, renewable energy system, equipment, and associated costs. OPEX costs include labour costs, maintenance, licenses, replacement equipment and any other related costs [12]. LCOH is a commonly used metric to compare hydrogen production technologies and investment allocations and decisions. It is a quantitative measure that estimates costs to various units of the production of hydrogen for the entirety of the system lifetime. By utilising the LCOH, it will assist in effectively indicating the economic feasibility of the technology and the value calculated will vary between the different technologies [13],[14].

V. METHODOLOGY

To evaluate the costs of producing green hydrogen powered by a hybrid solar and wind energy system, HOMER Pro software was used. The entire system was set up in Groblershoop, South Africa on the HOMER Pro software. The electric and hydrogen loads were selected. The renewable energies that were chosen for this system were solar (DC) and wind (AC) energy which powers the electrolyser. Other equipment that was selected was the converter and a battery, Fig.1.

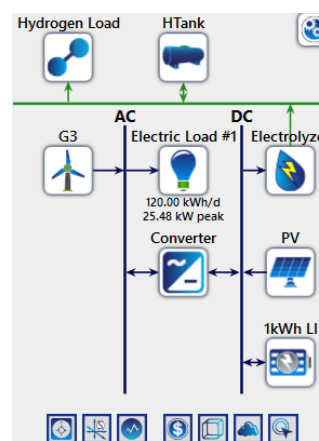


Fig. 2 Simulated system on HOMER Pro software.

The electric load and hydrogen load that was selected was 120KWh/d with the peak loads of 25.48KW and 25.48 kg/day respectively, which is tabulated in table 1. The electricity power required per day is 120 kWh/d and during the production of green hydrogen, the peak electricity load utilized is 25.48KW. The water electrolysis system was simulated to produce 120kg/day and the peaked amount of green hydrogen produced is 25.48kg/day.

TABLE I INPUT VALUES FOR ELECTRIC LOAD AND HYDROGEN LOAD

	Values	Units
Electricity load	120	kWh/d
Peak electric load	25.48	KW
Hydrogen load	120	kg/day
Peak hydrogen load	25.48	kg/day

Once the system was simulated, parameters such as hydrogen load, CAPEX, discount rate, electrolyser lifetime and the operating costs were used to calculate LCOH production.

$$LCOH \left(\frac{\$}{kgH_2} \right) = \frac{CAPEX \times Cr \times OPEX}{Pr \times 8760 \times C_f} \quad (1)$$

Where:

LCOH is the levelized cost of green hydrogen \$/kgH₂

CAPEX is the capital expenditure, \$

OPEX is the operating expenditure, \$

C_f is the capacity factor

Pr is the hydrogen production rate, kg/yr

The LCOH for transportation were calculated on Microsoft Excel. Hydrogen is stored in compressed gas tanks and is transported via trucks. Thus, costs were estimated relating to the transportation mode. Costs for hydrogen storage were simulated in HOMER Pro. Various sizes were selected for the optimisation process. For the feasible size that was chosen, an economic analysis was done on HOMER Pro for the size. The tank size ranged from 0 to 800kg (table II). The LCOH for hydrogen transportation was calculated using equation 2:

$$LCOH_{transport} = \frac{CAPEX_{terminals} + CAPEX_{transport}}{Delivered\ Hydrogen\ Quantity} + \frac{OPEX_{terminals} + OPEX_{transport} + fuel\ cost}{Delivered\ Hydrogen\ Quantity} \quad (2)$$

Where:

LCOH_{transport} is the levelized cost of hydrogen for transportation,

CAPEX_{terminals} is the capital expenditure of the terminals

CAPEX_{transport} is the capital expenditure for transport

OPEX_{terminals} is the operating expenditure of the terminals

OPEX_{transport} is the operating expenditure for transport

VI. RESULTS

The HOMER Pro simulation evaluated various configurations, and Table III presents the most feasible configuration. The rated capacity for the generic flat-plate PV was 700 kW, while each wind turbine at a height of 30m has a rated capacity of 3kW. Therefore, the provided required energy to produce green hydrogen while remaining within feasibility constraints, 100 wind turbines were selected. The maximum power needed for this system was 434 kW, and the generic 1kWh Li-Ion battery required 100 strings. The electrolyser size is 600kW and the hydrogen tank's size is 400kg. The economic analysis was therefore conducted based on this configuration, and the LCOH for hydrogen production was calculated. Capital expenditures were \$8,350,000 for the system (configuration) to be built, and operating costs for the entire system were \$385,365 (Table IV). The net present value of this system is \$14,032,370.00, and the levelized cost of electricity is \$21.72.

TABLE II THE FEASIBLE SYSTEM ARCHITECTURE

Parameter	Units	Values
PV	kW	700
Wind Turbines	Quantity	100
	kW	300
Battery	Strings	100
Converter	kW	434
Electrolyser	kW	600
Hydrogen tank	kg	400

Due to the feasibility of the system with a lifetime of 25 years, capital costs and operating costs were \$8,350,000 and \$385,365, respectively. The LCOH to produce hydrogen ranged between 16.98 and 24.998 \$/kgH₂. The LCOH was evaluated based off various factors that included the hydrogen produced every month for the entire year and the production of green hydrogen peaked during July.

TABLE III PARAMETERS FOR GREEN HYDROGEN PRODUCTION.

Parameter	Units	Values
CAPEX	\$	8,350,000
Operating costs	\$/yr	385,365
Discount rate	%	8
Electrolyser lifetime	yr	10
Capital recovery factor	-	0.149
Capacity factor	-	60
LCOH	\$/kgH ₂	16.98-24.998
LCOE	\$	21.72

The selected configuration for the 1kWh Li-ion battery was 100kWh. A capital cost of \$55,000 is required for the purchase of the battery with the operating expenses of 1000\$/yr. The annual throughput and losses are 4336kWh/yr and 457kWh/yr, respectively (Table V).

TABLE IV THE GENERIC 1KWH LI-ION BATTERY

Parameter	Units	Values
Rated capacity	kWh	100
Annual throughput	kWh/yr	4336
Losses	kWh/yr	457
Capital costs	\$	55,000
Maintenance costs	\$/yr	1000

The excess energy that was collected from the hybrid system was stored in the battery. The battery was 100 % full for the duration of the entire year (this is represented by the yellow legend). This indicated that there was sufficient energy for the entire system. During various hours of the day, there was a discharge of this energy. This indicated that the energy that was stored in the battery was used, especially in the early hours of the day and late at night (this is represented by the green/blue streaks). With the hybrid system being the primary energy source, the battery can therefore serve as a secondary or backup energy source during off-peak hours.

The input values for the hydrogen tank size ranged between 0 and 800kg on HOMER Pro. Once the simulation was complete, the feasible configuration was the 400kg size. Fig. 3 shows the fluctuations in the hydrogen stored over the course of a year. The amount of hydrogen stored started at 200 kg,

increased to 400 kg, and have fluctuated between 200 kg and 400 kg.

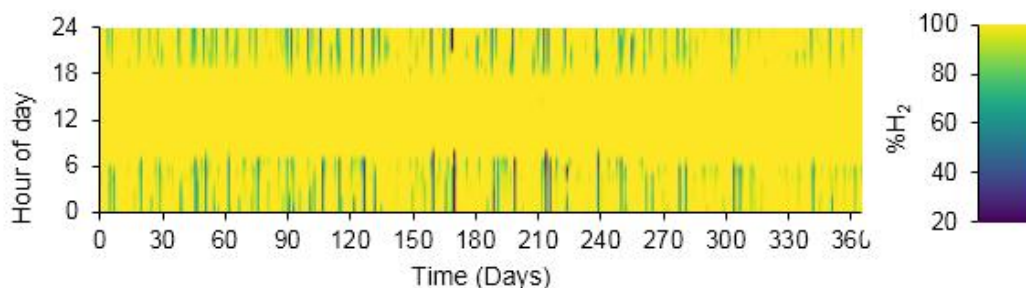


Fig. 3 Generic 1kWh Li-ion battery profile

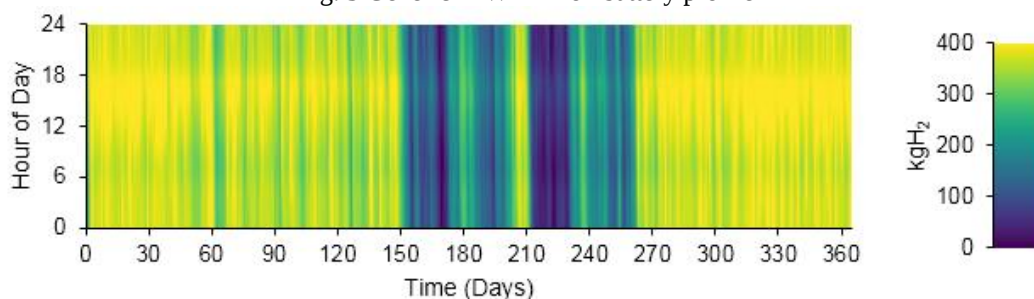


Fig. 4 Green Hydrogen tank profile

However, between day 150 and day 260, the hydrogen stored in the tank was roughly between 0kg and 250kg. From day 260 to the end of the year, the hydrogen stored in the tank was almost full in the hydrogen tank, with slight fluctuations throughout the year. At the end of the year, the hydrogen in the tank increased to 366kg. The tank's energy storage capacity is 13,333kWh (table VI). The capital costs allocated to the green hydrogen storage system were \$1,012,000.00.

TABLE V: HYDROGEN LEVELS IN THE HYDROGEN TANK

Parameter	Units	Values
Hydrogen storage capacity	kg	400
Hydrogen levels at the beginning of the year	kg	200
Energy storage capacity	kWh	13,333
Hydrogen levels at the end of the year	kg	366

The LCOH for green hydrogen transportation was calculated to be 3 hydrogen units transported by truck. At quantities of 240kg, 360kg, and 480kg, the calculated LCOH were 17.88 \$/kgH₂, 11.92 \$/kgH₂, and 8.94 \$/kgH₂, respectively. It was noted that, when the quantity of the transported hydrogen increases, the LCOH of green hydrogen transportation decreases.

TABLE VI: THE LCOH OF TRANSPORTING GREEN HYDROGEN.

	Units	Values		
Delivered hydrogen quantity	kg	240	360	480
LCOH _{transport}	\$/kgH ₂	17.88	11.92	8.94

VII. CONCLUSION

Conducting a techno-economic analysis of a study helps navigate and understand the feasibility of the studied technology. From HOMER Pro, only a specific configuration of the system is feasible. The capital costs for the green hydrogen system are \$14,032,370.00, which is a hefty amount. The operating costs of the system every year are \$385,364.60. The obtained results proposed a system configuration comprising an electrolyser of 600kW, powered by a hybrid wind and solar energy system of 600kW and 700kW, respectively, a generic 1kWh Li-ion battery of 100kWh, a converter with a rated capacity of 434k, and a hydrogen tank of 400kg. HOMER Pro is excellent software for simulating and optimizing renewable energy systems and for conducting a cost analysis of the system based on a feasible configuration. However, regarding costs, it mainly focuses on capital and operating costs, net present value, and LCOE, rather than LCOH, which is an important measure to calculate. Results obtained from HOMER Pro were therefore extracted and used in Microsoft Excel to calculate the LCOH for the production of green hydrogen. The LCOHs were calculated between the times when the hydrogen load was at its lowest and at its highest. The hydrogen production LCOH was 16.98 \$/kgH₂ and 24.998 \$/kgH₂.

The hydrogen tank was simulated to have a capacity of 400kg. This tank was efficient and sufficient, as hydrogen levels ranged from 0kg to 400kg without exceeding or pressuring the tank. The capital investment in the storage sector of this research was \$1,012,000.00. The LCOH for the transportation of green hydrogen was calculated for various quantities of hydrogen being transported. The selected quantities were 240kg, 360kg and 480kg. The corresponding LCOHs obtained were 17.88\$/kgH₂, 11.92\$/kgH₂, and 8.94\$/kgH₂, respectively. This indicates that more hydrogen being produced and delivered will cost per kg compared to less

hydrogen being produced and transported, where the prices rise. The total net present value of the system is \$14,032,370.00. The net present value was the sum of the equipment's (solar panels, wind turbines, electrolyser, battery, hydrogen storage tank and other necessary parts) cost. Each piece of equipment has its own capital cost (\$), replacement cost (\$), O&M cost (operation and maintenance) (\$) and salvage cost that are added together to get the entire cost of equipment for the entire system.

To further understand hybrid energy and its energy availability, more renewable energy sources will be introduced into the system. These renewable resources could be hydro, tidal etc.

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