Hydrogen for a Sustainable Tomorrow: Evaluating the Financial and Technical Dimensions of Green Hydrogen Production in South Africa – A Case Study in Ethekwini Municipality

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***Abstract* - Green hydrogen has emerged as a prominent approach in an effort to mitigate global warming. Given the urgency of addressing the climate change crisis and mitigating global warming, there is an increasing emphasis on curtailing carbon dioxide emissions. This can be achieved through the production of green hydrogen. While there are various renewable power supply options capable of being utilized for producing green hydrogen, this research focuses solely on offshore wind, photovoltaics (PV), and a hybrid solution due to eThekwini's perceived abundance of solar radiation and extensive coastlines with ample wind resources, making it highly conducive to renewable energy generation. This paper initially introduces the concept of Green Hydrogen production and outlines the methodology employed to assess the viability of hydrogen production from various potential sources. Additionally, the energy requirements for a typical hydrogen plant are determined, along with a brief discussion on potential sites. In this case study, an energy yield assessment was conducted for PV, offshore wind, and a proposed hybrid model to determine the most beneficial source and identify any technical issues that may arise from the utilization of the considered power supplies. Finally, a high-level financial assessment assessing the project's financial viability is described.**

Keywords— Decarbonization, Green Hydrogen, Offshore Wind, SDG-7, Solar Photovoltaics

I. Introduction

Hydrogen is widely regarded as a clean carrier of energy, implying it can store and be delivered in various forms such as green ammonia or methylcyclohexane [1]. Hydrogen can be extracted from natural gases such as methane and ammonia, utilizing different industrial processes. Alternatively, the molecular composition of water (H2O) can be fragmented during an electrolysis process to produce hydrogen. Green hydrogen is produced via the use of renewable energy in the form of wind, solar, and hydropower [2] [3].Currently, there are various industrial processes that utilize hydrogen on a large scale for different applications. These include hydrogenation, the Haber-Bosch Process, and hydrocracking [4] . As part of this effort, the utilization of hydrogen as a fuel is being supported, but only if it is produced in an environmentally conscious manner. The perceived colors are fundamentally associated with the fuel utilized in the hydrogen production process.

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This paper focused on green hydrogen. Table 1 illustrates the hydrogen color spectrum, showing the color that hydrogen is associated with relative to the feedstock required for production.

TABLE 1: HYDROGEN COLOR SPECTRUM REPRODUCED FROM [5]

Terminology		Technology	Feedstock	GHG Footprint
Production Via Electricity	Green Hydrogen	Electrolysis	Wind/Solar/Hydro /Geothermal/Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed Origin Grid Energy	Medium
Production Via Fossil Fuels	Blue Hydrogen	Natural Gas Reforming + CCUS	Natural Gas	Low
	Turquoise Hydrogen	Pyrolysis	Natural Gas	Solid Carbon (by-product)
	Grey Hydrogen	Natural Gas Reforming		Medium
	Brown Hydrogen	Gasification	Brown Coal	High
	Black Hydrogen		Black Coal	

It is essential to emphasize that we generate renewable green energy and convert it into hydrogen instead of directly harnessing electricity from renewable sources. This choice is driven by the superior efficiency of hydrogen fuel cells compared to various other energy solutions, including many green energy alternatives. Moreover, hydrogen fuel cells boast a significantly higher calorific value in terms of energy content as compared to other sources of energy e.g. coal, diesel etc. Notably, unlike batteries, hydrogen fuel cells do not necessitate recharging. When they are depleted, they will need to be replaced with a new hydrogen fuel cell [6].

This journal article aims to assess the viability of green hydrogen in the eThekwini region from both technical and financial perspectives, in alignment with our hydrogen strategy. Energy yield calculations of various methods are conducted to determine whether there are adequate resources for green hydrogen production. Financial analysis and modeling are also used to provide indicative projections.

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This assessment is crucial for determining whether the production of green hydrogen in the eThekwini region aligns with our broader hydrogen strategy and sustainability goals. By evaluating both the technical potential and financial feasibility, this study provides a comprehensive understanding of the region's capacity to support green hydrogen initiatives, offering insights that can guide future energy transition efforts.

II. Hydrogen Production Methods

Hydrogen is widely regarded as one of the most abundant elements in the universe; however, it fails to present itself in an elemental form on Earth or in the atmosphere due to its small molecular mass. Hydrogen in its natural elemental form must be produced from other hydrogen compounds. These compounds include fossil fuels, water, and forms of biomass. A source of energy, such as thermal (heat) and electrolytic (electricity), is needed for each production technique.

A. Steam Methane Reforming

The steam methane reforming (SMR) technology produces hydrogen utilising a reaction of a hydrocarbon such as methane gases with water. The methane reacts with the steam under the presence of some type of catalyst to produce Hydrogen (H_2), Carbon Monoxide (CO) and minimal quantities of Carbon Dioxide (CO_2). Heat is required to facilitate this reaction, making it an endothermic reaction. The design of the hydrogen manufacturing plant plays a significant role in the purity of hydrogen produced.

B. Electrolysis

Electrolysis utilises electrical energy to fragment water molecules (H_2O) into their elemental form i.e., Hydrogen and Oxygen. This process is accomplished by the use of an anode and a cathode whilst passing an electrical current through water as shown in Figure 1.

During the electrolysis process, two water molecules react at the cathode by acquiring two electrons, which then produce hydrogen gas (H_2) and hydroxide ions (OH-). Whilst, at the anode, two other water molecules break down into oxygen gas (O_2) and release four H+ ions, along with the flow of electrons into the cathode. The surplus oxygen gas, which is a valuable industrial gas with applications in processes like combustion, semiconductor manufacturing, and wastewater treatment, can be utilized. Eventually, the H+ and OH- ions combine and neutralize each other, forming water molecules again. The electrolysis process is summarised in Equation 1 below.

$$2H_2O + Electricity = 2H_2 + O_2 \quad (1)$$

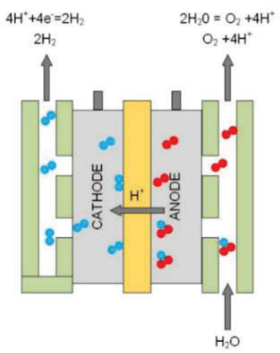

Fig. 1. Electrolytic processing of water to form hydrogen (reproduced from [7])

III. Limitations of Green Hydrgen in Ethekwini

A. Infrastructure Challenges

eThekwini presently lacks the necessary infrastructure to produce, store, and transport hydrogen at a large scale. Establishing a hydrogen production network requires significant investment in specialized infrastructure such as electrolysers, hydrogen pipelines, and storage facilities

B. Water Availability

Green hydrogen production requires substantial amounts of water for electrolysis. eThekwini, like other parts of South Africa, faces water scarcity issues. This is why water desalination technology was incorporated. Saltwater cannot be electrolyzed directly as it would result in competing reactions that may make the process inefficient or pose a safety hazard.

C. Policy and Regulatory Barriers

In South Africa, policies and regulations for green hydrogen development are still in their infancy. Without clear guidelines, incentives, and support from the government, the development of green hydrogen projects in eThekwini may be slow.

IV. Methodology

In this study, possible renewable power supplies were compared in terms of energy yield and technical parameters such as voltage regulation, harmonics, and fault currents.

The Cato Ridge area and Richards Bay were identified as potential hydrogen corridors. However, given that the Durban port (Durban is a city in the eThekwini Municipality) stands as the busiest on the African Continent, it holds a pivotal position in fostering economic growth within the province and the nation at large. These factors underscored the rationale for conducting this research within the eThekwini region [8]. It is further noted that the eThekwini Municipality has emerged as the first South African metropolitan municipality to develop a regional hydrogen strategy [9].

The electrolysis process requires significant amounts of electricity, and this study determined whether renewable power supplies have the capacity to supply power to these electrolysers based on the availability of renewable resources within the eThekwini region. In this assessment, electrolysis was the method that was utilized to produce hydrogen.

Figure 2 illustrates the high-level methodology employed in assessing the viability of green hydrogen production in the eThekwini Municipality. The flowchart outlines a structured approach for the development of a hydrogen plant. It began with the development of technical specifications for the hydrogen plant, which was followed by the Hydrogen Plant Site Selection process. After the site was selected, three design options were considered: Photovoltaic (PV) Design, Offshore Wind Farm Design, and Hybrid Design. Each design approach was subjected to Energy Yield Simulation Studies, which assessed the potential energy output. Subsequently a financial analysis was conducted for each design, evaluating metrics such as Net Present Value (NPV), Life Cycle Cost, and Pay Back Period. Finally, the viability of each design path was compared to determine the most feasible option for the hydrogen plant.

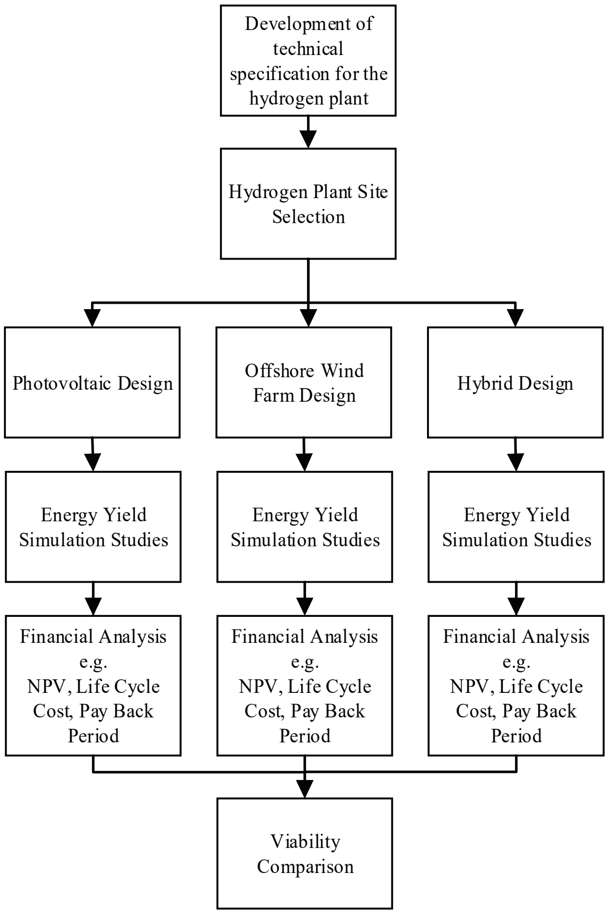

Fig.2. Project Methodology Flow

V. HYDROGEN PLANT DESIGN SPECIFICATION, POWER SUPPLY AND LOCATION

A. Hydrogen Production Plant Autonomy and Output Requirements

It was envisioned that, based on the operation time of the plant and electrolyser specification utilized on other international projects, the plant should be able to produce a minimum of 2000 kilograms (kg) of hydrogen a day (based on power delivery capability).

Based on a typical hydrogen electrolyser requirement [10], the plant would require approximately 20,000 litres of water to achieve this output. The current water crisis in the eThekwini municipality and the projected scarcity of fresh water in the future necessitate that the plant would be most sustainable using desalinated water [11]. When saltwater is electrolyzed directly, competing reactions occur. Chlorine gas is produced at the anode instead of oxygen, and sodium hydroxide (NaOH) may also form. These potential side reactions make the process inefficient and can pose safety hazards due to the release of toxic chlorine gas. Hence, we concluded that this is not safe for green hydrogen production.

Table 2 provides a summary of the electrical requirements that any renewable power supply ought to satisfy for this specific green hydrogen plant.

TABLE 2: ELECTRICAL REQUIREMENT SPECIFICATION FOR HYDROGEN PLANT.

Electrical Requirement	Specification
Power	15 MVA
Voltage (Based on Typical Electrolysers available in Industry)	11 kV

B. Green Hydrogen Power Supply Requirements

The green hydrogen power supply must meet the following criteria:

- ❖ The cumulative power requirements inclusive of compressors, cooling and electrolyser arrays [12].
- ❖ The distinct power demand of the hydrogen electrolyser array [12].
- ❖ The harmonic profile at the point where the renewable power supply couples with the transmission board is known as the point of common coupling (PCC). This should be in compliance with IEEE 519 [13]

C. Green Hydrogen Production Plant Location

The hydrogen plant location is highly dependent on various factors. A site suitable for green hydrogen production requires :

- ❖ Large quantity of water for use as feedstock for hydrogen electrolysis
- ❖ Large physical footprint for site establishment
- ❖ Access to significant amount of green energy

The Cornubia industrial area and the Port of Durban were both carefully considered as potential locations for the hydrogen production plant.

The port was selected as an area of interest because there are current plans for expansion and growth as per the Transnet KZN ports master plan strategy [14]. Additionally, there was a high availability of space at the port to facilitate the production plant. The port would also ensure ease from an export perspective for the hydrogen produced.

The Cornubia industrial area (North of Durban) was also an area of interest due to its significant industrial growth in recent times and the availability of land. After careful consideration of these factors, the Cornubia industrial area was chosen.

The Cornubia industrial area was seen to be more beneficial for the following reasons:

- ❖ The risks of tidal surges and flooding are significantly reduced as the Cornubia industrial zone is not in close proximity to water as compared to the port.
- ❖ The hydrogen produced is intended for export and the plant is in close proximity to the Dube trade port, thus allowing a convenient and cost-effective shipment of the hydrogen to international markets.
- ❖ Typically, industrial areas have established regulatory frameworks for industrial activities. This can

streamline the permitting process and ensure compliance with environmental and safety regulations.

- ❖ Co-locating hydrogen production with other industrial processes can enable the utilization of waste streams, such as heat or byproducts, creating a more efficient and sustainable operation.

VI. Renewable Power Supply Viability and Sizing

A. PV Viability and Plant Sizing

In designing the PV system to be integrated with the proposed hydrogen production factory, it is crucial to first assess the feasibility of PV at the specific location. It was interesting to note that if the plant were located in another part of South Africa that had a higher solar insolation, such as the Northern Cape, then a much smaller PV plant would have been required to generate the same amount of power. However, finding an abundant and available water source in these areas could prove to be a challenge. Figure 3 illustrates the Global Horizontal Irradiation (GHI) of South Africa. Although it is evident that Durban is typically on the lower end of the irradiance scale, with an average GHI of approximately 4.6 kWh/m2, it was nonetheless deemed favourable for the proposed solar farm.

In comparison with Germany which currently has one of the highest solar power outputs globally, it is noteworthy that Germany has a GHI of 3.6 kWh/m2 [15] and this highest observed in the country with consideration to the various regions in the country. Despite eThekwini having the lowest GHI in the entire country, it still surpasses Germany's GHI. Germany has some of the largest solar farms globally, hence the comparisons of the GHI's emphasis the viability of PV technology in eThekwini.

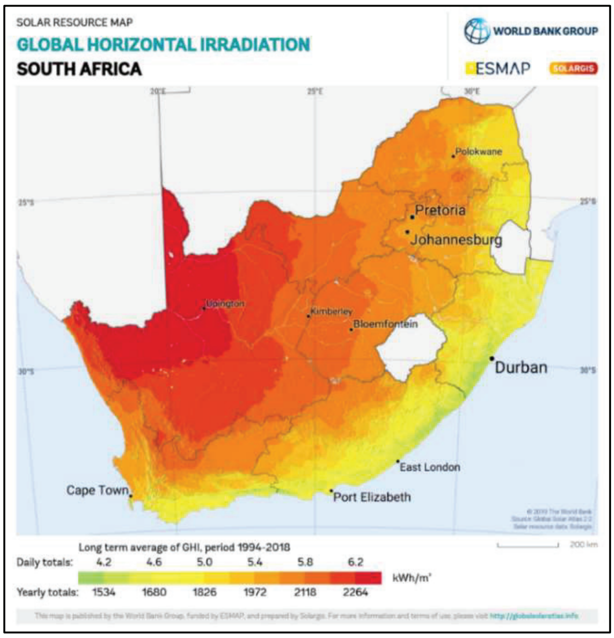

Fig. 3. Global Horizontal Irradiation [16]

When sizing the solar PV farm, it is crucial to consider both the loading requirements and the time period. In the case of the potential hydrogen plant, 14.3 MVA is required for the plant to operate.

The plant was expected to operate for a duration of 9 hours, starting from 8 am and concluding at 5 pm. The required plant load for the 9-hour duration is 128.7 MWh/day and should be provided by the PV array.

Next, this power requirement was scaled up to accommodate typical losses with the PV system and the losses that occur during the DC/AC transformation. The scaling factor used, as commonly recommended, is 1.25. Hence, the PV array is required to provide approximately 160.8 MWh per day for the operation period of the plant.

Solar energy is only available at certain parts of the day, and the number of sun hours is represented by the solar insolation factor. The insolation factor for the Cornubia area is approximately 4.6 as per the GIS dataset utilized. This indicated there are 4.6 sunshine hours during the day.

The power of the solar array can be approximated by utilising Equation 2.

$$P = \frac{E_{array}}{Solar\ Insolation} = \frac{160.8\ \text{MWh}}{4.6} \approx 35\ MW \quad (2)$$

Hence the total PV array required is 35 MW. In this study the intention is to only assess the capacity of the PV system and not design the required solar plant from the perspective of sizing the number of parallel and series strings.

B. Offshore Wind Viability and Plant Sizing

Figure 4 illustrates the wind speeds at various locations along the coastline of South Africa.

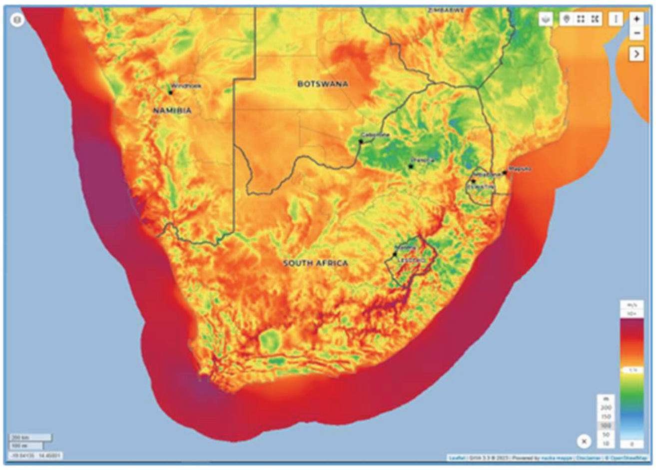

Fig. 4. Wind Speeds Along the Coastline of South Africa [17]

The estimated wind speed required for an offshore wind farm to be viable is 6 m/s [18]. Figure 4 demonstrates the wind speeds along the coast of Durban, and the wind speeds are consistently at or above 9 m/s, making wind energy a viable option. The wind speed was assessed at 100m above ground, which is the typical height of the hub of wind turbines.

Figures 5 and 6 depict the monthly and hourly variations in wind speed, respectively, as represented by the wind speed index derived from an average wind speed of 9.54 m/s. The wind speed index is the variation of wind speed from the average wind speed. It is noticeable that both graphs exhibit occasional decreases in wind speeds, however these reductions are relatively minor and are still conducive to power generation.

The wind turbines have the ability to generate power for the majority of the day and night. This, in turn, could potentially be leveraged to double hydrogen production and enhance the overall financial payback periods. Alternatively, excess power may be sold to the utility at night.

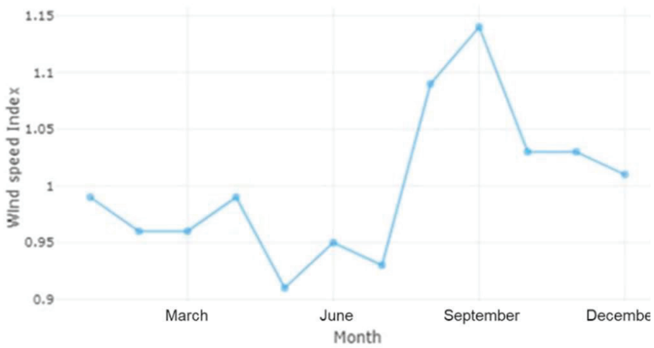

Fig. 5. Monthly Variation in Wind Speed [17]

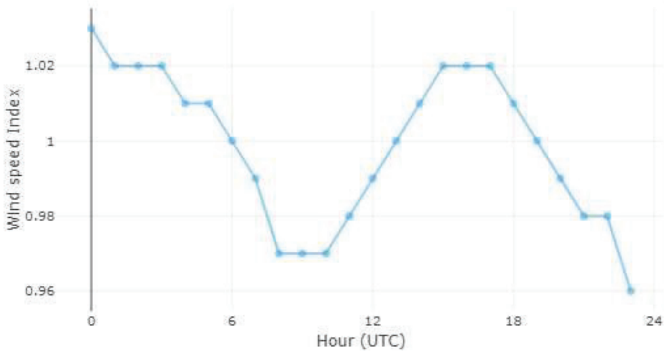

Fig. 6. Hourly Variation in Wind Speed [17]

The proposed hydrogen production facility had a power requirement of 14.3 MVA. To accommodate potential energy losses during transmission and other operational inefficiencies, the wind turbine array was designed to generate electricity at a capacity that exceeds the actual power consumption. Figure 7 shows the power curve of a typical 8 MW wind turbine.

Based on the power curve of a standard turbine operating at an average wind speed of 9.4 meters per second, approximately 5.5 MW of power can be expected from each turbine. To accommodate potential energy losses during transmission and other operational inefficiencies, the wind turbine array was designed to generate electricity at a capacity that exceeds the actual power consumption. Specifically, the wind turbine array was sized to produce 20% more electricity than the 14.3 MW required.

To fulfil the 14.3 MW power requirement of the hydrogen production plant, it would theoretically necessitate roughly 3.1 turbines. However, for the sake of reliability and to account for potential wind speed fluctuations, it is advisable to install 4 turbines. This arrangement does result in some overcapacity; nevertheless, the surplus power can be efficiently exported to the grid.

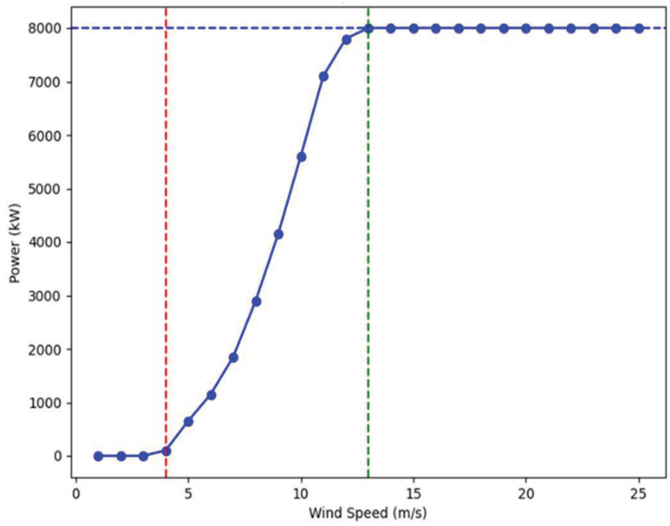

Fig. 7. 8MW Wind Turbine Power Curve

C. Hybrid Solution

The integration of renewable energy sources, particularly solar and wind power, presents complementing benefits. While solar photovoltaic (PV) systems offer clean energy generation, they are subject to intermittency due to weather conditions. On the other hand, offshore wind turbines provide a more consistent power supply but face challenges such as higher installation costs and maintenance requirements.

Considering these factors, it is proposed that a hybrid solution also be considered, combining both PV and offshore wind technologies., Initially two wind turbines was utilized to complement a PV farm that was half the size of the plant that was originally designed utilizing only PV.

VII. Energy Yield Analysis

A. Solar PV

To determine the potential PV yields resulting from varying irradiance levels, PVsyst SA, a solar design software, has served as a valuable tool in this research. PVsyst harnesses meteorological data from multiple years to construct a comprehensive weather dataset, enabling the calculation of expected hourly yield per day.

Figure 8 illustrates the normalized average monthly energy yield. The required monthly yield for the facility to operate for a full month equates to 4050 MWh, based on having nine operational hours per day. The normalized production exceeds this requirement. This surplus can be viewed as a significant benefit, as the excess electricity (when available) can be exported to generate revenue. This, in turn, effectively reduces the payback period for the investment.

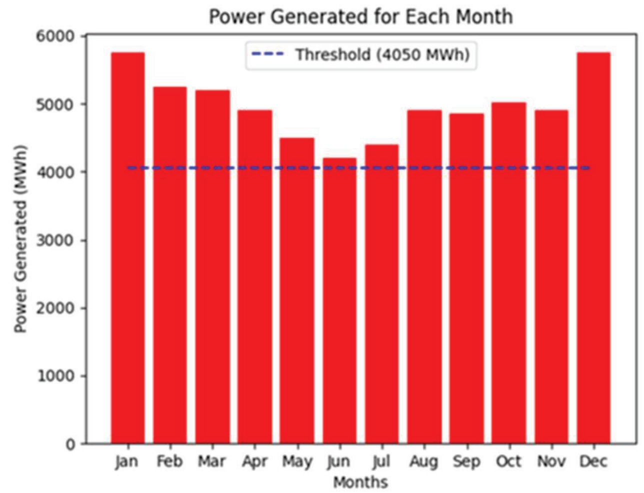

Fig. 8. Normalized PV Generation per month

The facility is anticipated to maintain a continuous power demand of 14.3 MW per hour. It is crucial to acknowledge that PV energy generation adheres to a theoretical normal distribution curve. This signifies that the majority of power generation will coincide with peak sunlight hours. However, there will be instances when adequate power generation may not occur. Consequently, the incorporation of Battery Energy Storage Systems (BESS) becomes a necessity for the PV option to ensure a consistent and dependable supply. To precisely determine the optimal size of the BESS, it is imperative to monitor the plant's load behaviour based on the normal distribution pattern. Table 3 provides data on plant hourly generation generated by PVsyst and can be used to determine the required size of the BESS system. In this table, the operation time is shown, the times highlighted in red show periods where the plant is not operational, and the light green show the times when the plant is operating. The dark green shows the times when there is sufficient generation for the plant, while the light red regions show insufficient generation at that particular time.

TABLE 3: PV HOURLY GENERATION IN MWH

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6H	4	2	1	0	0	0	0	0	1	4	5	5
7H	10	8	7	6	5	4	3	5	8	10	10	11
8H	17	14	14	13	12	10	10	12	14	16	15	17
9H	21	19	19	19	18	16	16	17	19	19	18	20
10H	24	23	22	22	21	20	19	21	21	22	20	22
11H	23	24	23	23	22	22	21	23	22	22	20	22
12H	22	25	23	23	22	22	22	23	22	20	20	22
13H	20	24	22	21	19	20	20	21	20	18	19	20
14H	18	21	19	17	15	15	16	17	16	15	16	17
15H	15	17	14	12	9	9	10	11	11	11	11	13
16H	10	11	8	5	3	1	4	5	5	5	7	8
17H	4	4	2	0	0	0	0	0	0	1	2	3

Referring to the data presented in Table 3, it becomes apparent that there is an energy deficit during late afternoons and early mornings, while there is an energy surplus during peak solar conditions, which can be exported to the grid.

To address this energy imbalance, a BESS is necessary, to accommodate the morning and afternoon energy demand. To determine the size of this system, it should be noted that the power generation for June should be utilized as it is the worst-case scenario for periods when BESS is required.

It can be seen that in the month of June during the following periods there is a deficit of power required, as shown below:

- At 8:00, the deficit amounts to 4.3 MWh, calculated as the difference between 14.3 MWh and 10 MWh.
- At 15:00, the deficit amounts to 5.3 MWh, calculated as the difference between 14.3 MWh and 9 MWh.
- At 16:00, the deficit amounts to 13.3 MWh, calculated as the difference between 14.3 MWh and 1 MWh.

At 8:00, 15:00, and 16:00, there was a recorded combined deficiency of 22.9 MWh of generation during the operational period. There was 4 MWh available during this period of deficiency to provide some charge to the BESS system in the morning. The size of the BESS is given in equation 2.

$$22.9\ MWh - 4MWh = 18.9\ MWh \quad (3)$$

The large BESS capacity was attributed to the absence of overnight charging. The BESS implementation utilized lithium-ion batteries due to their inherent advantages and a lower depth of discharge, specifically at 20%. Consequently, the BESS must be designed with a capacity that exceeds the required power by 20%, resulting in a total capacity of 23 MWh.

B. Offshore Wind

The performance of a wind turbine relies on the speed of the incoming wind. However, it is important to note that the power generated is not directly proportional to the wind velocity. Each turbine operates uniquely. To ascertain the output of a particular turbine at a given wind speed, referencing its power curve becomes essential. In this wind yield assessment, the wind analysis is conducted using the Python code, which estimates the power output of an array of wind turbines.

The average wind speed identified offshore in eThekwini is approximately 9.4 m/s. This indicates that each turbine produces an instantaneous power of 5.5 MW.

Figure 9 provides the instantaneous power generated by the wind array per month. It is noted that the hydrogen plant required 14.3 MW, and this can be provided by the wind turbine array for the entire year. It is noted that the power provided is significantly lower in the drier months compared to the rainy spring months such as September. The instantaneous power curve shows a strong correlation between the wind speed and the instantaneous power produced.

The monthly yield required for the facility to run autonomously for a full month is 4050 MWh. However, it is observed from the energy yield analysis that there is excess generation, which now proves advantageous. This surplus, compared to solar energy, is due to the availability of wind almost 24 hours a day, whereas solar energy is only accessible for approximately 4.6 hours. This surplus energy can be effectively utilized to extend the factory's operational hours. Due to wind being more available, the requirement for BESS and storage becomes obsolete.

Moreover, a significant advantage of this wind-based solution is that if there is surplus energy even after the factory's operations, it can be sold to neighbouring industrial facilities, thereby generating additional profits. It can be seen that for a green hydrogen production facility in the eThekwini region, a wind solution from an energy yield perspective is better than employing a solar PV solution.

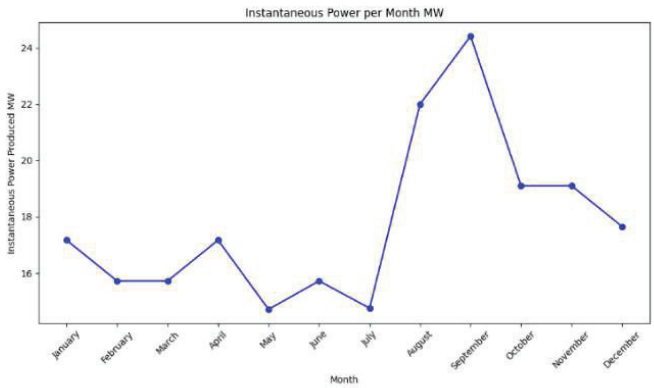

Fig. 9. Offshore Wind Power Instantaneous Power Generation

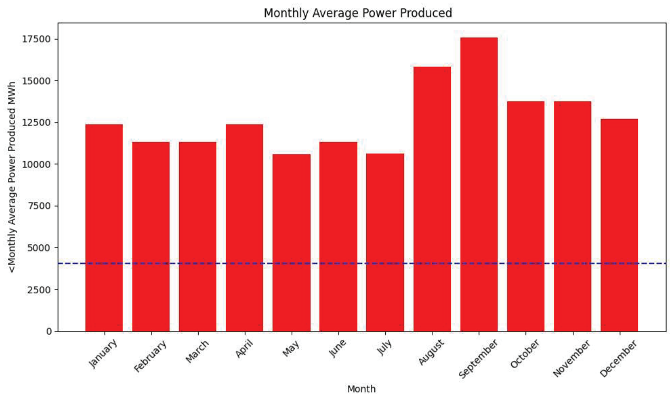

Fig. 10. Offshore Wind Farm Annual Energy Yield

C. Hybrid Solution

Figure 11 provides a graphical representation of the energy generation of the hybrid solution proposed.

Even though it can see be seen that the two wind turbines provided the generation capacity required, they cannot function independently because, they cannot provide the instantaneous power of 14.3 MW as required. This is the primary reason the systems have to be oversized.

This depiction highlights the complementary nature of the hybrid model, where the strengths of each energy source compensate for the other's limitations, resulting in a reliable and sustainable energy supply. It is noted with a hybrid solution that the design is optimized, provides a generation capacity that is not excessive.

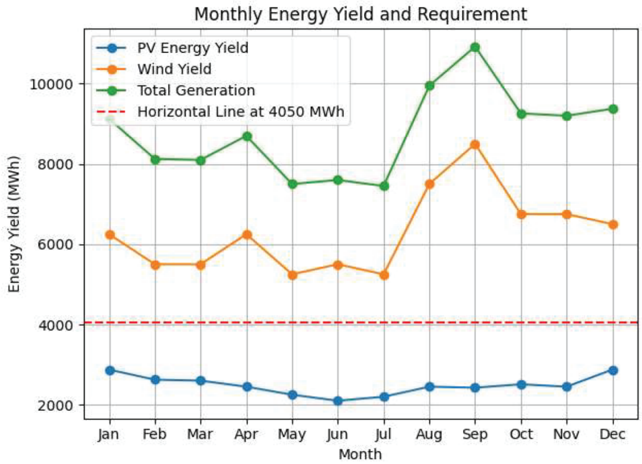

Fig. 11. Hybrid Energy Production Yield

VIII. Financial Analysis

This section aims to evaluates the financial viability of various renewable energy options for powering a green hydrogen production plant. In this financial analysis, the methodology in Figure 12 was utilized.

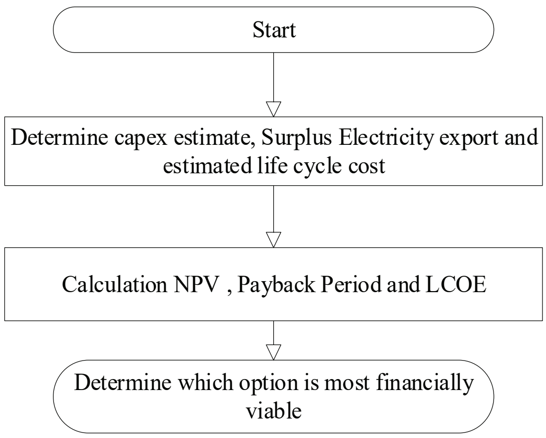

Fig. 12. Financial Viability Flow Chart

In the financial analysis the following assumptions were made:

- The rand dollar exchange rate used was R 18.30/ $ as on the 12th of January 2024
- The export tariff utilized in the modeling was R 1.04 per kWh. This tariff was adopted from the City of Cape Town, as eThekwini does not currently have a tariff structure in place for private power purchase. The City of Cape Town is comparable to eThekwini Municipality and has a high uptake of Independent Power Producers (IPP).
- The hydrogen export price utilized was R 50.20 per kg [19].
- The financial model takes into consideration that with the PV power supply, only half the quantity of hydrogen can be produced as compared to utilising an offshore wind farm power supply. This is due to the available operation hours of the plant.

A. Capital Expenditure (CAPEX) Estimate

The estimated CAPEX breakdown for the various power options considered are detailed in Figures 13 – 15. The CAPEX for a renewable energy source involves considering various factors such as equipment costs, installation expenses and infrastructure. For solar projects, this includes the costs of solar panels, inverters, and installation labor, while offshore wind projects also include foundation costs. Estimating the capital CAPEX for a renewable energy project involves considering various factors such as equipment costs, installation expenses, infrastructure, permitting fees, and financing costs. For solar projects, this includes the costs of solar panels, inverters, and installation labor, while offshore wind projects also include foundation costs. The estimated CAPEX utilizes current industry rates.

When these components are aggregated the total CAPEX cost per the power supply type is as shown in Table 4.

TABLE 4: CAPEX ESTIMATE

Power Supply Option	Cost (Million Rands)
PV Model	R 810 M
Hybrid Model	R 1,367 M
Offshore Wind farm	R 2,108 M

The primary reason for this substantial difference in costs lies in the inherent factors associated with each technology.

- ❖ The construction and installation of offshore wind turbines in marine environments are complex and require specialized equipment and expertise, leading to increased expenses in manufacturing, transportation, and installation, compared to solar PV.
- ❖ The development of necessary infrastructure such as undersea cabling and substations for transmitting electricity from offshore wind farms to onshore locations significantly contributes to the overall CAPEX.
- ❖ Offshore Wind Turbines are significantly more expensive than PV panels and inverters.
- ❖ Identifying and securing suitable offshore sites for wind farm development may involve additional surveying, permitting, and regulatory compliance costs compared to solar projects on land.
- ❖ The installation of offshore wind turbines involves specialized vessels, equipment, and skilled personnel, contributing to higher installation costs. Moreover, maintenance and operational costs for offshore wind farms are typically higher due to the challenging marine environment and the need for regular inspections and repairs.
- ❖ Offshore wind turbines require additional investment in grid infrastructure, such as subsea cables and specialized substations, to transmit energy from offshore locations to the main grid. PV systems can often connect directly to existing grid infrastructure, particularly in distributed rooftop installations, reducing integration costs.
- ❖ Offshore wind projects often face stringent environmental impact assessments, permitting requirements, and marine wildlife considerations, which can add time and costs. While PV installations also undergo permitting, the process is generally simpler and less costly, especially for ground-mounted PV farms on previously cleared land.

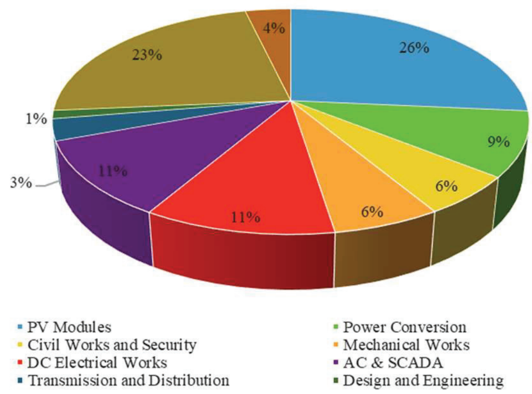

Fig. 13. PV Capital Cost Breakdown

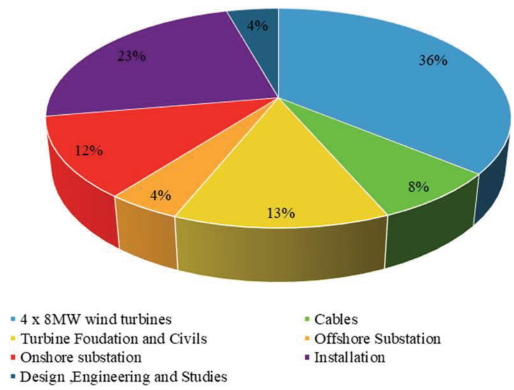

Fig. 14. Offshore Wind Farm Capital Cost Breakdown

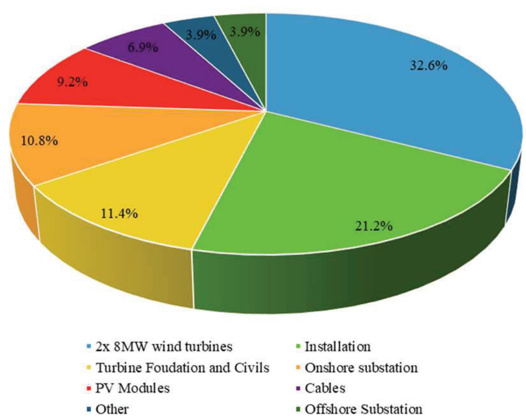

Fig. 15. Hybrid Model Capital Cost Breakdown

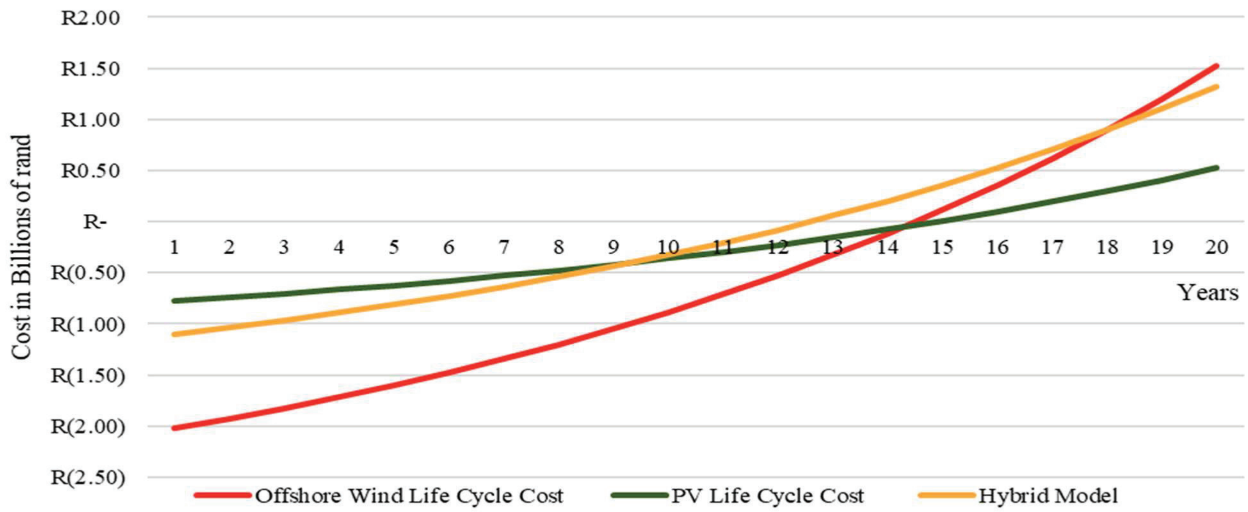

Fig. 16. Life Cycle Costing of Hydrogen Production Plant Power Supply Options

Figure 13, Figure 14 and Figure 15 present the breakdown of the CAPEX for various components within each of the power supply options. These figures provide the allocation of CAPEX for different items associated with each power generation option. It can be seen that the PV panels and inverters and the wind turbines form the largest part of the CAPEX in each power supply.

The hybrid model, composed of solar PV and offshore wind, is more complex due to it having two independent energy supplies. Its CAPEX is 68% higher than solar PV but 64% lower than a stand-alone offshore wind farm. This indicates the economic advantages of the hybrid approach despite its increased complexity

B. Revenue Generated

This revenue is calculated using the Equation 4

$$Revenue = Power\ Export + Hydrogen\ Export \quad (4)$$

The analysis revealed that the revenue generated from utilizing an offshore wind power supply, amounting to R 130,649,600 exceeds that of the PV power supply (R 48,809,60 by a factor of 2.67. This considerable disparity in revenue is primarily attributed to the offshore wind power's capability to produce twice the amount of hydrogen.

Moreover, the offshore wind farm not only generates substantial revenue from hydrogen production but also contributes to additional income by producing surplus electricity. This surplus is exported to local industries through export, further enhancing the revenue stream of the offshore wind power supply.

In assessing the hybrid solution, it can be noted that the energy provided at night from the turbines is able to facilitate the operation of one electrolyser at night, with the surplus being exported into the local eThekwini grid. The calculated revenue generation is R89,729,600, which was 84% greater than that of PV (R48,809,600) and 31% less than that of an offshore wind farm (R130,649,600).

C. Life Cycle Cost

The total life cycle cost for the various power supply options is given in Table 5 for a 20-year period:

TABLE 5: TOTAL LIFE CYCLE COST IN RANDS

Power Supply Option	CAPEX	Operations & Maintenance	Revenue	Total Life Cycle Costing
PV	R 810 M	R 664 M	R 2,000 M	R 526 M
Hybrid	R 1,367 M	R 1,196 M	R 3,678 M	R 1,114 M
Offshore	R 2,108 M	R 1,778 M	R 5,356 M	R 1,519 M

Figure 16 illustrates the life cycle costing of the various supply options considered on a single set of axes. It is evident that the offshore wind system provides a more favourable life cycle cost after 20 years. It is important to note that the growth is exponential indicating a larger increase in life cycle costing over time.

D. Key Financial Indicators

In assessing the financial indicators, the NPV analysis strongly favors the offshore wind option, with its NPV being 2.88 times greater than that of the PV solution. All three-options exhibit positive NPVs, indicating promising investments. It is noted that the hybrid solution has the fastest payback period.

Moreover, the wind solution has a 7% greater ROI compared to the PV, Whilst the hybrid model shows an 82% return on investment over 20 years. Based on the above indicators, the hybrid alternative is the more viable alternative. Table 6 provides the key financial indicators

TABLE 6: KEY FINANCIAL INDICATORS

Financial Indicators			
	PV	Hybrid	Offshore Wind
NPV	R 164 M	R 347 M	R 473 M
Payback Period	15 Years	12.5 Years	14.5 Years
ROI	65%	82%	72%

E. Levelised Cost of Energy

Levelized Cost of Energy (LCOE) is a metric used to assess and compare the cost of generating electricity from different sources over the lifetime of a power plant. It represents the average revenue per unit of electricity required to recover the costs of building and operating a generating plant, including the cost of capital, fuel, maintenance, and other factors.

The levelized cost of energy can be computed as shown below:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t.el}}{(1+i)^t}} \quad (4)$$

Where:
I_0 – Initial Investment in Rands
A_t – Annual total cost of operation
$M_{t.el}$ – Produced amount of energy in kWh
i – Interest rate
n – Period Years

In calculating the LCOE for these three alternatives, the following assumptions were made:

- The period considered for the LCOE calculation was 20 years.
- An interest rate of 6% was utilized.
- Annual operational costs and the amount of energy produced were incorporated into the life cycle costing calculations.

As shown in Table 7, with a LCOE of R 1151.33, the hybrid system offers a competitive alternative that combines the advantages of multiple generation sources. This approach can enhance reliability and resilience by leveraging both solar and other potentially renewable energy sources.

Moreover, hybrid systems may better accommodate varying energy demand patterns and local conditions, potentially offering greater flexibility and adaptability in energy generation. Therefore, while solar PV is appealing from a cost perspective, the hybrid solution presents a compelling case by providing a balanced approach that addresses various factors beyond just LCOE.

TABLE 7: LEVELIZED COST OF ENERGY

Power Supply Option	LCOE (per MWh)
Solar PV	R 960.01
Offshore Wind	R1,094.31`
Hybrid	R 1151.33

IX. CONCLUSION

In conclusion, when considering energy yield, it becomes evident that the three solutions examined in this case study are capable of providing the energy required to produce green hydrogen. However, the hybrid solution stands out by offering a balanced yield. This balance makes the hybrid solution the preferred choice from an energy yield perspective.

Furthermore, from a financial standpoint, while various power supplies may dominate specific areas, the hybrid solution demonstrates a balanced performance across different financial indicators. This balance, encompassing aspects such as cost-effectiveness, return on investment, and operational efficiency, confirms the hybrid solution as a favourable option from a financial perspective as well.

Thus, for a holistic and efficient approach, the hybrid (wind and solar) system proves to be the most favourable option for the production of green hydrogen in the eastern corridor of South Africa.

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