Techno-economic Analysis of a Wind/ Solar PV Hybrid Power System to Provide Electricity for Green Hydrogen Production

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Green hydrogen (GH) is recognized as a fundamental pillar in shaping a sustainable global future. The process involves the hydrolysis of water with sustainable electrical sources. This paper presents a techno-economic assessment of hybrid renewable wind and solar power systems in Yanbu, Saudi Arabia, to provide clean energy to enhance carbon-natural petrochemical operations. The implementation of Energy Compensation Policies, such as Net Energy Metering or Net Energy Billing Mechanisms, has a substantial influence on the financial viability of GH Plant. The present research compared the impact of such a mechanism on the levelized cost of Energy (LCOE) and the Levelized cost of Hydrogen (LCOH). The study recommended the adoption of a Net Metering Mechanism as a highly efficient strategy to encourage private sector investment in renewable energy production in the Kingdom of Saudi Arabia (KSA). This approach was found to be effective, resulting in an accumulated electricity tariff of 26.5 $/MWh and a levelized cost of hydrogen (LCOH) of 1.65 $/kg.

Keywords: *Green hydrogen, renewable energy, solar PV energy, wind energy, net metering, net billing, energy policies*

1. INTRODUCTION

The rapid change in conventional fuel prices and equally depleting reserves have accelerated the deploy–ment of renewable energy (RE) projects. Continuous improvement of renewable technologies has resulted in the cost-effective implementation of such projects. On the other hand, the severe aftermath associated with the bur–ning of fossil fuels, which results in greenhouse gas (GHG) emissions, has motivated the world to take orga–nized steps towards reducing GHG emissions. The UN Climate Change Conference COP 21, Paris Agreement, is a legally binding treaty adopted by 196 countries on climate change. The Paris Agreement aims to limit the rise in global temperature to well below 2°C by empo–wering investment in renewable energy resources utili–zation. According to the REN21 2022 report, rene–wable resources supplied almost 12.6% of the total global energy in 2020 [1].

Although known for its large oil reserves, the Kingdom of Saudi Arabia (KSA) has adopted several initiatives towards sustainable development and the utilization of renewable resources for power generation. In 2021, HRH Crown Prince Mohammed bin Salman announced the Saudi Green Initiative (SGI), which aims to chart a greener future by clearly defining an ambi–tious road map that rallies the Kingdom and signi–ficantly contributes to achieving the set global targets in confronting climate change.

The wind and solar photovoltaic (PV) technologies are technologically mature and commercially acceptable for profitable implementation. The electricity produced from renewables can be used for water electrolysis to produce green hydrogen. Hydrogen is categorized into three main types based on the energy source used for its production. The first type is called gray hydrogen, produced using fossil fuels such as natural gas, coal, and oil, resulting in high CO_2 emissions. Second is the blue hydrogen, which is supplemented by a carbon capture unit that results in less carbon emissions. Finally, green hydrogen is produced from the water electrolysis pro–cess using electricity from renewable resources. Nowa–days, 98% of the produced hydrogen comes from natural gas or coal energy, which is a CO_2-intensive process. Hydrogen production accounts for CO_2 emis–sions of around 830-million-ton CO_2 per year. However, the demand for hydrogen has grown more than three times since 1975 [2]. Hydrogen can contribute to the future of green energy as an alternative energy source in its pure form or after it's converted into hydrogen-based fuels (ammonia, synthetic methane).

The chemical industry is crucial in developing novel strategies that facilitate the transition toward sustainable development and a circular economy. The achievement of the net-zero aim is reliant on many strategies, inclu–ding energy efficiency, bio-based feedstock carbon cap–ture, and electrification in the petrochemical sector. It is crucial to understand that these measures alone are not sufficient, highlighting the need for additional solutions such as Green and Blue hydrogen. Within the environ–mental context, the utilization of free CO_2, hydrogen, and its associated by-products will assume a pivotal

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position as a sustainable fuel source for energy-intensive processes and applications. These hydrogen derivatives will be sustainable raw materials for the petrochemical and chemical sectors.

Hydrogen can serve as a substitute for natural gas and other conventional fuels to power industrial burners and boilers. Therefore, offering a source of carbon neut–ral heat source for industrial operations.

The Eastern Region of Saudi Arabia has the nece–ssary infrastructure to establish a blue hydrogen industry, including the production, refining, and petrochemical sectors associated with oil and gas. This infrastructure can also support the implementation of carbon capture, utilization, and storage (CCUS) technologies. On the other hand, the Kingdom has abundant solar and wind resources, which can be harnessed to generate cost-ef–fective electricity to produce green hydrogen. The NEOM project, located in the northwest region, is cur–rently home to a large-scale green ammonia production facility, anticipated to be one of the world's largest.

The present research evaluates the financial aspects of implementing renewable energy sources (RES) for supplying green energy to Yanbu petrochemical plants, which rely on conventional energy sources. To evaluate the feasibility of a green hydrogen plant, the present work aims at designing a hybrid renewable energy system to satisfy 571 MW of electricity demand for a hydrogen plant with a production capacity of 100 kta.

2. LITERATURE REVIEW

Martinez and Iglesias [3] used the levelized cost of energy (LCOE) to study the feasibility of energy developments in the Mediterranean Sea and identified potential sites for the deployment of floating wind turbines. Dabar et al. [4] evaluated the potential of wind energy for generating +1700 GWh/year of electricity and green hydrogen in the Republic of Djibouti. Wind speed characteristics were examined using wind measurements taken at five weather stations over five years to determine the levelized cost of energy (LCOE) and levelized cost of hydrogen (LCOH). The study reported that the cost of power generation was lower than the local electricity prices, and green hydrogen production was reported to be relatively competitive.

Due to an increase in electricity prices in the Canary Islands, utilization and integration of RES were proposed by Qiblawey et al. [5] to reduce CO_2 emissions and the cost of energy (COE). Alharthi et al. [6] used HOMER software to analyze the technical and financial aspects of the grid-connected hybrid system and determined the potential for the utilization of environmentally friendly energy sources in many cities in Saudi Arabia. The findings demonstrated that Yanbu city was more financially and ecologically viable than the other chosen cities, with the lowest net present cost (NPC) and LCOE [6].

Singlitico et al. [7] investigated the possibilities of producing green hydrogen from different RES and found the lowest COE for wind energy. The findings demonstrated that green hydrogen was priced competitively with conventional technologies while lowering power bills. Shah et al. [8] used several software programs along with meteorological measu–rement to identify windy potential sites in Pakistan for developing the wind farms and found that Sothgun was the most appropriate site for wind farms development with the lowest payback period and highest total yearly carbon reduction potential.

A general overview of renewables status and the forecast on a global scale was discussed in the REN21 2022 status report [1] and the IEA 2021 report [9]. Also, the same agenda was discussed by AL-Douri et al. [10] for Saudi Arabia in terms of opportunities and chal–lenges. They emphasized the development of solar energy applications, both isolated and grid-connected, in the main cities such as Riyadh, Dammam, and Jeddah. Owhaib et al. [11] studied solar potential in Jordan and identified Ma'an City as a feasible site for solar power plant development. The results indicated that the proposed location in Ma'an was highly favorable, with an average annual capacity factor of 32.2%.

Edalati et al. [12] presented the techno-economic assessment of grid-connected PV systems in Jordan and Iran and found similar characteristics as in Saudi Arabia. Khatri [13] and Shukla et al. [14] presented the technical design and economic assessments for standa–lone rooftop PV systems for residential buildings. According to IEA, the interest in the water electrolysis process is growing due to the significantly declining costs of renewable technologies in general and wind turbines and solar photovoltaics in particular, which improved the feasibility of green hydrogen production. Currently, three electrolysis technologies are commer–cially available, with an average efficiency of 61-80% [2]. For further reading on wind power utilization in different parts of the world, readers are suggested to explore these publications [15-21].

KSA is blessed with high intensities of solar radia–tion and longer hours of sunshine duration and hence becomes a potential candidate for harnessing solar ener–gy. Global Solar Atlas shows the country gets around 2200 kWh/m^2 irradiance annually [22]. Saudi Arabia has some regions with promising wind resources for utility-scale wind farms, and its first utility-scale wind farm of 400 MW capacity in Dumat Al Jandal has been connected to the grid [6]. This wind farm is expected to deliver power to around 72,000 households in the region.

3. METHODOLOGY

The examination of several parameters is necessary to determine the best location for a wind farm, solar PV farm, or both in a given geographic area to provide energy to a green hydrogen plant (GHP). The metho–dology covers (1) metrological data collection, (2) GHP assessment, and (3, 4) techno-economic assessment of wind and photovoltaic resources, see Figure 1. Software is utilized to benchmark and validate the excel-based model to identify re-potential at the designated location and conduct an economic assessment to determine the LCOE. Additionally, a compensation assessment is conducted to find the optimal case with the lowest electricity tariff and the LCOH of hydrogen production per kg.

4. AUDI RENEWABLE ENERGY FRAMEWORK

4.1 Energy Compensation System

For a robust grid management process, the grid operator must regulate the integration of self-consumption of distributed energy resources to achieve grid stability. There are two energy compensation systems that give individuals credit for excess energy production, i.e., net billing and net metering. In a net metering system, the credit gained by excess energy is saved in a unit of energy, meaning that whenever energy is imported from the grid, the consumer will pay only for the net energy amount. In this way, the kilowatt-hour (kWh) produced by the prosumer is precisely the kilowatt-hour energy imported from the grid.

The net billing system gives individuals the ability to sell the surplus energy produced by their systems to the grid at the same wholesale rate. In this system, the energy generated by prosumers is treated just like ener–gy produced by utility companies, and it's a monetary exchange system, meaning that the amount of money will be deducted from the prosumers' monthly bills.

Saudi Arabia has decided to apply the net billing electricity strategy with a feed-in tariff of 5 HH/kWh for the commercial sector and 7HH/kWh for the residential sector. In July 2023, the Saudi Water and Electricity Regulatory Authority (WERA) updated the regulatory framework for self-consumption in a way that encou–rages electricity generation from distributed renewable energy resources. The new framework has mandated obtaining certain permits from the authority and other entities before the installation of renewable energy systems to ensure compliance with SASO (Saudi Stan–dards, Metrology, and Quality Org.) codes.

4.2 Energy Distribution System

Saudi Arabia has launched several initiatives towards the ambitious target of being a carbon-neutral country by 2060. However, the high renewable penetration into the national network comes with multiple challenges. The intermittency of renewable resources is one of the biggest associated challenges. In order to mitigate the effect of renewables integration issues, the transition into a distri–buted grid concept has to be opted for. The distributed grids are the future of electricity grid management in which electricity can flow in two directions while connecting multiple small-scale producers to the grid.

Those producers could be households and apartment buildings with rooftop solar PV systems, commercial buildings with solar PV systems, or even waste management/handling companies with biomass energy. Allowing multiple power producers to inject clean energy into the grid will improve the electricity sector's carbon footprint. However, in order to encourage individuals to invest in their own renewable energy units, the government has to plan for an encouraging policy that could include higher feed-in tariffs or adapting the net banking compensation system.

5. HYDROGEN PRODUCTION-TECHNICAL ASSESSMENT

5.1 Hydrogen Systems Design

The production of hydrogen with a low carbon footprint may be achieved by the utilization of fossil fuels and chemical processes, such as steam reforming. This method involves the separation and capture of the resulting CO_2 as a by-product, which can be stored in–definitely or used in chemical manufacturing. This process is often referred to as Carbon Capture and Storage or Use (CCUS). In this particular scenario, a considerable percentage of carbon dioxide (up to 90%) is mitigated. Other methods, such as biological and nuclear processes, exist to produce zero-carbon hydrogen. However, the prevalent approach is water electrolysis, which uses energy generated by wind and/or solar sources [23]. The hydrogen generated by the process of electrolysis exhibits a high level of purity, hence eliminating the need for the removal of CO and CO_2, often required in hydrogen production using steam methane reforming methods, Equation 1 [24].

$$H_2O(l) \rightarrow H_2(g) + {}^1\!/_2\, O_2(l) \tag{1}$$

While examining Yanbu's meteorological data, it becomes evident that both wind and solar energy exhibit favorable conditions for the production of hydrogen via the process of electrolysis. Solar energy is suitable for DC power transmission to minimize costs related to power electronics and AC-DC conversion [25]. In regions where solar or wind or both resources are exploitable in good quantities, the COE generation could go below \$30.5/MWh. With this cost of energy and substantial plant size, the cost of hydrogen could be below \$2.03/kg.

5.2 Green Hydrogen Plant Assumptions and Sizing

Approximately \$752 million is needed to invest in the production of 100 kT of green hydrogen. The OPEX and Maintenance (MTCE) budgets are determined by calcu–lating 5% and 2.5% of the CAPEX (Table 1), respec–tively. Other researchers projected a potential de–crease in the cost of hydrogen production to \$1.48 per kg by the year 2030, depending upon the reduction of renewable energy costs [26]. The electricity cost is assumed to be the minimum possible in this assessment to reduce the levelized cost of hydrogen (LCOH) production.

Table 1. Basic Economic Parameters

Parameter	Unit	Value
CAPEX	\$ Mn	752
OPEX	% of Capex	5
Maintenance	% of Capex	2.5
Debt in total investment	%	70
Equity in total investment	%	30

The Alkaline Electrolysis Cell (AEC) technology is appropriate for large-scale electrolysis. The electrolysis process is assumed to be 11.1% efficient. The energy consumption is considered as 50 kW/kg of hydrogen yield. The hourly production rate of hydrogen is taken at approximately 11.4 kg. The product is assumed to be free of impurities and is sent to the Deoxygenation unit if necessary. Apart from that, there are no additional processes, and the hydrogen produced is compressed for transportation to the process plant [27].

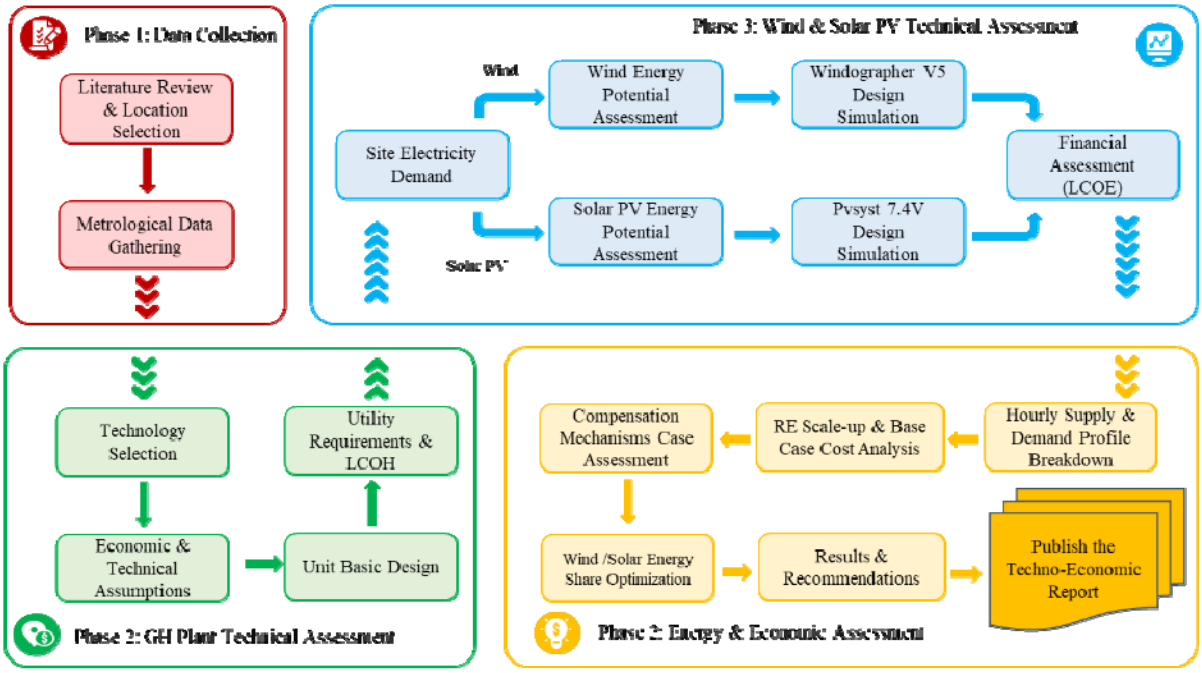

Figure 1. The methodology used to conduct the Techno-economic assessment for GHP

5.3 Wind Resources Assessment

For accurate assessment of resources, wind speed and wind power characteristics are analyzed in detail to understand the annual, monthly, and diurnal variability and availability for successful/profitable implementa–tion of wind power plants at the selected location. The characteristics include mean wind speed, wind po–wer density (WPD), wind turbulence, prevailing wind direc–tion, wind shear, wind power, and plant capacity factor (PCF): the wind speed, direction, and other meteoro–logical data for the selected location in Yanbu City. The data was processed using Windographer software, a state-of-the-art wind data analysis tool. The software also estimated the wind power, energy, and Plant Capa–city Factor (PCF) for a chosen type of wind turbine.

The wind shear factor (α) refers to the change in wind speed with height and is affected by the rough–ness of the surroundings. The wind shear is calculated using the following formula:

$$\alpha = [\ln(V2) - \ln(V1)] / [\ln(Z2) - \ln(Z1)] \qquad (2)$$

where V1 and V2 are the wind speeds in m/s at heights Z1 and Z2 in m, the variation of wind speed at different hei–ghts can be calculated accurately based on the local wind shear exponent, as obtained above. The wind shear expo–nent obtained using the wind speed data at different heig–hts at the location under consideration is shown in Figure 2.

Weibull probability distribution is a statistical method used to analyze wind speed data. This distribu–tion is widely used to describe the wind speed data accurately and provides the frequency distribution. Weibull distribution is expressed as follows:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)e^{-\left(\frac{v}{c}\right)^k} \qquad (3)$$

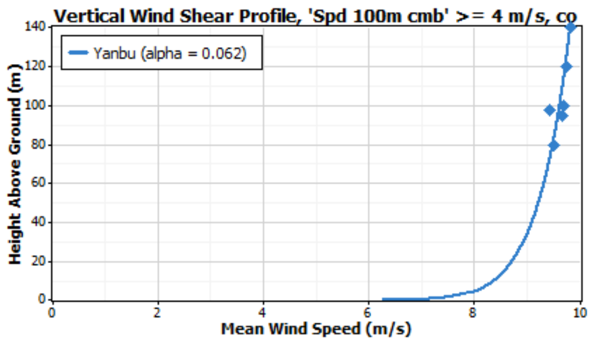

Figure 2. Wind shear profile at the project location

where k and c are the shape and scale parameters. The shape parameter is dimensionless and describes the slope of the distribution curve. The scale parameter c shows how strong the wind is at a selected location and is measured in m/s. The Weibull distribution parame–ters obtained for the selected site are used to fit the measured data, see Figure 3. The Weibull shape para–meter values are 2.33 and 2.255 at 80 m 120 m heights, while the corresponding scale parameter values are 9.859 m/s and 9.622 m/s. As observed from Figure 4, the monthly mean wind speed values at different heig–hts (80 to 140 m) do not increase visibly, and no seaso–nal trend could be seen at this site. Overall, the wind speed if found to increase from January till September and then decreased towards the end of the year. The maximum and the minimum wind speeds are observed in September and October. The wind rose diagram confirms that the prevailing wind direction at Yanbu is from NW.

Wind power density (WPD) is known as the amo–unt of power that can be produced per square meter of rotor area (W/m^2). It is a function of air density (ρ) and a cube of wind speed (V). It can be expressed by the following equation:

$$WPD = \frac{1}{2}\rho V^3 \qquad (3)$$

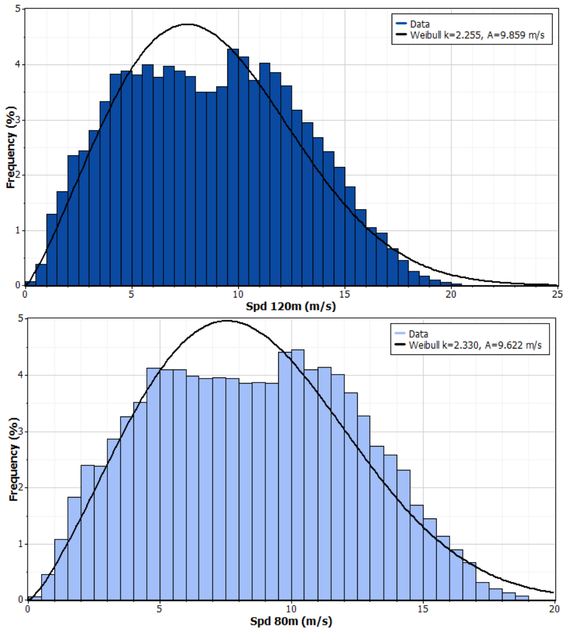

Figure 3. The Weibull probability distribution for wind speed at 80 and 120 m height

Hence, precise and accurate measurements of wind speed are required to properly estimate the WPD at any location. The wind speed increases with height; hence, the hub height must be optimized between power gene–ration and the costs related to tackling the installation and structural issues. Figure 4 shows the monthly mean wind speed at 80, 120, and 140 m heights. Indeed, the mean wind speed shows a small variation between 120 and 140 m, making the 120 height favorable hub height. Overall, the monthly mean wind speed at different heights varies between a minimum of 6.25 m/s and a maximum of 9.75 m/s, corresponding to the October and November months of the year. The prevailing wind direction at the Yanbu site is seen to be prevalent from North West direction, Figure 4.

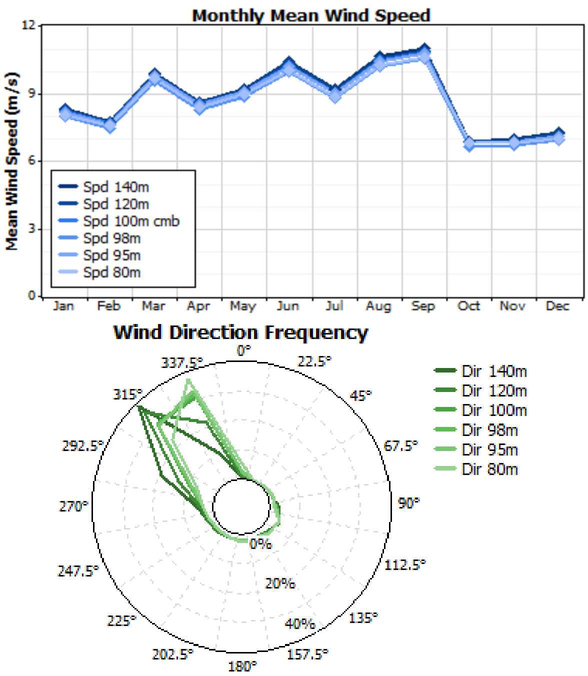

Figure 4. Monthly mean wind speed and wind direction frequency distribution at different heights

The wind energy is extracted through wind turbine blades, and a maximum of 59.3% of the wind power can be converted into mechanical power. The wind power can be calculated as follows:

$$P = \frac{1}{2}\rho C_p A_t V^3 \tag{5}$$

where Cp is rotor efficiency, and A_T is the rotor area in m^2. Another important parameter related to wind tur–bines' performance is the capacity factor (CF). It is de–fined as the ratio of actual energy yield (AEY) and the maximum possible energy that could be produced based on the rated capacity of the wind turbine. The capacity factor can be calculated using the following simple equation:

$$CF = \frac{Annual\ Energy\ production\left(AEP\right)}{Maximum\ Energy\ production} \tag{6}$$

Most of wind turbines have capacity factors ranging from 36% to 50%. For a particular location, the capacity factor can vary depending on the rotor diameter, hub height, cut-in, and rated speeds of the wind turbine. A comparison among different wind turbines was carried out in terms of power output and CFs, considering the mentioned parameters. The analysis indicated the suitability of the GAMESA wind turbine G136-4.5MW wind turbine with 120 hub height for the site under consideration. The wind power curve of the selected wind turbine is provided in Figure 5.

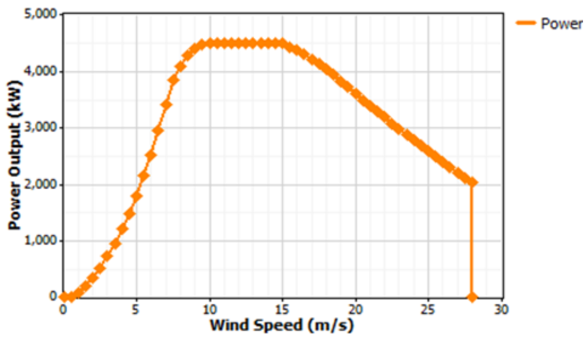

Figure 5. GAMESA G136-4.5MW wind turbine power curve

For economic analysis of the wind farm, the equity and debt discount rates are assumed as 12% and 4%, respectively, Table 2. The escalation rate of rise in ope–rations and maintenance (O&M) is considered as 2.5%, whilst the plant's operational life is considered as 25 years.

Table 2. Wind power economics' basic parameters

Parameters & Assumptions	Value
Equity Discount rate	12%
Dept Discount rate	4%
Debt ratio	75%
Equity ratio	25%
WACC	5.55%
Escalation rate	2.5%
Terminal Value	10%
Load factor	49.8%
LCOE	13.26 HH/KWh 35.36 $/MWh
Tariff	13.70 HH/KWh 36.55 $/MWh

The LCOE for the proposed system is determined to be \$35.36/MWh, whereas the electricity tariff rate in Saudi Arabia is \$36.55/MWh (Table 2). The wind turbine cost is considered to be \$1059/kW, as shown in Table 3. The total cost for the equipment and installation of a single wind turbine amounts to \$6.88 million. The system incurs a cost of \$40/kW for its operation and maintenance.

Table 3. Wind turbine cost parameters

Item	Cost
Wind Turbine Cost (\$/KW)	1,059
System Balance Cost (\$/kW)	331
O & M Cost (\$/kW)/Year	40

5.6 Solar PV Farm and PV Module Specifications

Solar PV panels are devices that directly convert solar radiation energy into direct current. Global horizontal irradiance (GHI) is the total solar energy collected on a horizontal surface, and it is usually measured on a monthly or yearly basis (Figure 6). The GHI indicates the potential of solar energy at any location, and its value can be obtained from different resources and software. The present study used PV SYST version 7.4 software to simulate the PV output and other economic and technical aspects. The meteorological data was obtained from the software's database for sizing and designing the grid-connected PV power plant. Saudi Arabia is blessed with a high density of solar energy in most locations. The geographical coordinates of the site are summarized in Table 4.

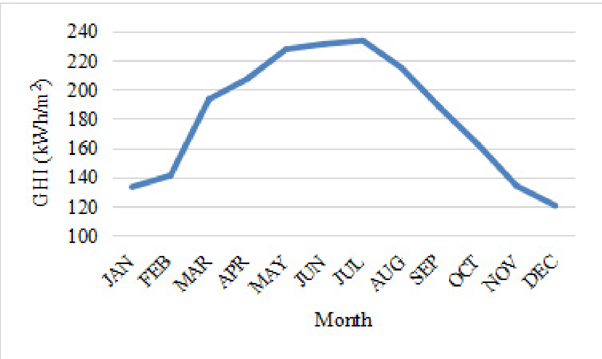

Figure 6. Monthly mean global solar radiation (GHI) at Yanbu

Table 4. PV farm location parameters

Parameter	Value
Latitude (Ø)	24.3 °N
Longitude	37.5 °E
Optimum title angle	30
Operating hours	2037
Average annual solar radiation (kWh/m^2)	2187.1

The PVsyst simulation results indicate that for each block, 476 strings of 27 modules must be installed in series. This system will require a total of 12,852 PV modules, which will be implemented on an area of 33.2 km^2 in total. System losses associated with the panels and the inverter are evaluated and resulted in a performance ratio of 87.30%. The technical specifications of the inverter and the block are provided in Tables 5 and 6; respectively.

Table 5. Inverter specifications

Inverter Specifications	
Power rating (kW)	185
DC voltage input (V)	1080
AC voltage output (V)	600
Amplitude modulation index, Ma	0.87
Frequency modulation index, Mf	100

Table 6. Block Summary

Block Summary	
Number of modules	12,852
Number of strings	472
Number of arrays	119
Number of nnverters (NI)	40
PV block power (kW)	7,000
Performance Ratio (%)	83.70

The starting point in the block simulation is to select price-competitive and efficient PV modules that can deliver the desired power. The number of DC blocks (NM) required and expected string power (SP) output are calculated using the following simple equations:

$$NM\left(Modules\right)=\frac{V_{idc}}{V_{mpp}} \tag{7}$$

$$SP\left(W\right)=NM*P_{mpp} \tag{8}$$

Next, a suitable inverter type is from Huawei (Model: SUN2000-185KTL-H1). The specifications are given in Table 5. The modulation index (Ma) was adjusted at 0.870 to meet the required AC voltage of 600 V. Finally, the number of inverters (NI) per block was calculated according to equation 10.

$$V_{idc}=2\sqrt{2}\times\frac{V_{ll}}{\sqrt{3}*M_a} \tag{9}$$

$$NI=\frac{IP}{AP} \tag{10}$$

The economic evaluation of the photovoltaic (PV) or any other such system depends on the equity and debt discount rates, the annual escalation rate of O&M costs, the anticipated project life. These and other related parameters are given in Table 7. The LCOE for the system is calculated to be 20.61 \$/MWh while the tariff rate of electricity in KSA is 22.72 \$/MW. The carbon credit incentive is also considered in this project evaluation.

The cost of the PV module is taken as \$99.6 per unit, with overall cost of complete block of \$1.28 million. The cost of each inverter is taken as \$3,400 and a total of 40 inverters are required for the entire block (Table 8). The inverter has a lifespan of 10 years and the expenses associated with its replacement are included in the overall project cost. The operational and maintenance cost of the system is considered as \$10/kW.

Table 7: Solar PV basic economic parameters

Parameters & Assumptions	Value
Equity Discount rate	12%
Dept Discount rate	4%
Debt ratio	75%
Equity ratio	25%
WACC	5.55%
Escalation rate	2.5%
Terminal Value	10%
Load factor	22.51%
LCOE	7.73 HH/KWh
	20.61 \$/MWh
Tariff	8.52 HH/KWh
	22.72 \$/MWh

Table 8: Solar PV system component costs

Item	Per item	Per block
PV module cost - \$	99.6	1,280,310
Inverter cost - \$	3,400	136,000
Mount cost - \$	806	287,742
System O/M cost – \$/kW	10	70,000

6. RESULTS

6.1 Base Case Energy Analysis

One of the key objectives of this study is to determine the effective sizes for the PV farm and the wind farm to fulfill the energy requirements of the proposed GHP. The primary goal is to decrease the dependence on power from the grid to achieve a smooth transition to RES. The following criteria is used in the present analysis:

- The energy needs of GHP is considered to be 571 MW
- The provision of site power needs must also be facilitated by RES being the primary source while the grid serves as a secondary backup supply.
- The electricity distribution infrastructure has the capacity to provide and absorb renewable energy at high rates.
- The determination of the total quantity of PV blocks and wind turbines necessary to fulfill the demand for GHP is derived from the following equation:

$$\begin{aligned}&GH_{demand}\left(MWh\right)=Block_{SolarPVGen}\left(MWh\right)*\\&*Blocks(\#)*\alpha+Turbine_{WindGen}\left(MWh\right)*Turbines\left(\#\right)*\beta\end{aligned} \qquad (11)$$

where:

α= Share of solar PV energy (%)

β= Share of Wind energy (%)

The share of electricity supply is distributed evenly between PV and wind where:

- 50% of the energy generated is derived from 192 solar photovoltaic (PV) blocks.
- 50% of the energy generated is derived from 137 wind turbines.

In order to mitigate carbon dioxide emissions, it is essential that the local production of electricity from renewables should exceed the quantity imported from the grid at the conclusion of the calendar year.

The allocation of system share is considered to be based on the use of the lowest net electricity tariff.

The process of selecting an appropriate size includes the MTCE plans and an additional 7% capacity margins.

To fulfill the GHP demand ($E_{GH\ Required}$), the electricity will be supplied through RE (PV-E_{PV} and Wind-E_{WT}) sources during the day, while the grid will make up during nighttime in addition to the energy available from the wind, if any. The grid contribution can be calculated using the following relationship:

$$E_{Grid}=\begin{cases}E_{GHRequired}-\left(E_{WT}+E_{PV}\right), & E_{GHRequired}>\left(E_{WT}+E_{PV}\right)\\ 0, & E_{GHRequired}<\left(E_{WT}+E_{PV}\right)\end{cases} \qquad (11)$$

The difference between total demand ($E_{GH\ required}$) and renewable energy supply (E_{WT} + E_{PV}) is considered when setting up the system's power/energy balance. The following condition defines the (E_{Net}) parameter:

$$E_{Net}=\begin{cases}E_{RENet}=E_{NET}<0\\ E_{GridNet}=E_{NET}>0\end{cases} \qquad (12)$$

where:

$E_{RE\ Net}$ = RE systems provide most of the electricity to GHP

$E_{Grid\ Net}$ = Grid systems provide most of the electricity to GHP

The hourly average available energy from PV and wind for the Yanbo site is shown in Figure 7. The resulting data show a higher PV energy (E_{PV}) supply from the 8th to the 16th hour, during which time GHP demand can be satisfied by RES. However, after sunset, the GHP will receive partial power from the grid depending on the power available from the wind. The monthly mean power production from wind and solar sources is provided in Figure 8. It is evident that wind power fluctuates more in nature than solar power. The wind power varies between a minimum of 1.79 MW in October and 2.79 MW in November. So, absorbing such fluctuations becomes a challenge for the application, in this case, the GHP. However, during the rest of the months, the average power output is observed to remain around the annual mean value (Figure 8).

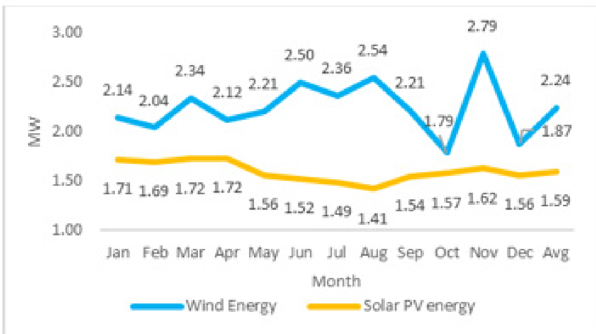

Figure 7. Average hourly variation of solar and wind energy availability

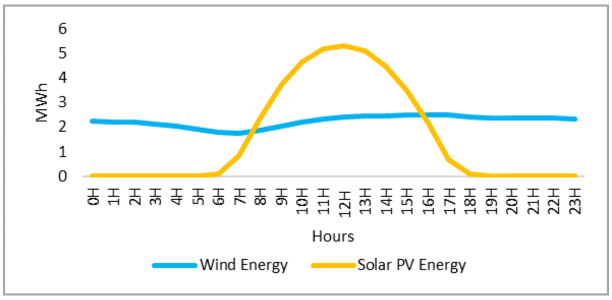

Figure 8. Average Monthly estimation of hourly energy generation for idevedual solar PV block and wind turbine

Renewable sources are expected to produce more electricity than is needed to operate the GHP to be carbon neutral. The following condition-based equation is used to calculate the surplus electricity generated by renewable sources ($E_{\text{Excess Gen.}}$), as follows:

$$E_{ExcessGen} = \begin{cases} 0, & E_{Net} > 0 \\ -E_{Net}, & E_{Net} < 0 \end{cases} \tag{13}$$

The RES produced the maximum energy of 453.1 GWh in the month of March, while the GHP demand was 424.7 GWh, Table 9. Since the energy needs of GHP are constant throughout the year, hence it can be said that renewable sources can meet this demand during most of the months, as summarized in Table 8. Consequently, the grid system will provide the additional energy required to meet this demand during the months when there is a shortage of renewable power availability.

Table 9. Energy supply and demand from RES, Grid, and GHP

Items	GH Deman d	Scaled-up 50% Solar & 50% Wind	Import from Grid	Netload	Excess Energ y
Month	$E_{\text{GH Required}}$	$E_{PV}+E_{WT}$	E_{Grid}	E_{Net}	E_{Excess}
	GWh /Month				
Jan	424.7	432.5	136.3	-7.8	144.1
Feb	384.2	379.1	127.1	5.1	122.0
Mar	424.7	453.1	116.3	-28.4	144.7
Apr	411.0	418.1	127.2	-7.0	134.2
May	424.7	418.4	125.2	6.3	118.9
Jun	411.0	426.9	102.7	-15.9	118.6
Jul	424.7	424.2	117.9	0.6	117.4
Aug	424.7	431.2	108.1	-6.5	114.6
Sep	411.0	403.2	123.0	7.9	115.1
Oct	424.7	380.9	154.4	43.9	110.6
Nov	411.0	467.6	91.3	-56.6	147.9
Dec	424.2	386.5	152.9	37.6	115.2
Year	5,000.8	5021.6	1482.5	-20.7	1503.3

6.2 Base Case Cost Analysis

The economic analysis is conducted based on the costs of the energy imported from the grid, total energy generated by PV and wind resources, and the surplus available for export to the grid after meeting the power requirement of the GHP. The LCOE is used to measure the cost associated per kWh of energy generated from RES and is calculated as follows:

$$LCOE = \frac{\begin{array}{c}\textit{the present value of the whole cost incurred} \\ \textit{during the lifetime}(SAR \textit{ or } \$)\end{array}}{\begin{array}{c}\textit{The present value of all electricity} \\ \textit{generated through the lifetima}\end{array}} \tag{14}$$

The power imported from the national grid is priced at 0.18 SAR/kWh, represented by T_{Grid}. However, if the demand is lower than the electricity generated by the RES, there will be no import from the grid:

$$C_{Gtrid} = \begin{cases} -E_{Net} \times T_{Grid} & E_{Net} > Zero \\ 0, & E_{Net} > Zero \end{cases} \tag{15}$$

The solar photovoltaic and wind tariffs are referred to as T_{PV} and T_{Wind}, respectively. The cost of hybrid energy (C_{hybrid}) is calculated using the tariffs for solar (T_{PV}) and wind (T_{Wind}) energy via the following equation:

$$C_{hybrid} = E_{PV} \times T_{PV} + E_{WT} \times T_{WT} \tag{16}$$

In order to determine the overall expenditure on electricity exported (C_{Export}) to the grid, the following equation is used:

$$C_{export} = \begin{cases} -E_{Net} \times T_{feed-in} & E_{Net} < Zero \\ 0 & E_{Net} > Zero \end{cases} \tag{17}$$

In this equation, the net access electricity (E_{Net}) required to run the GHP is used. The cost of the electricity exported to the grid, considering the feed-in tariff ($T_{\text{Feed-in}}$) of 0.05 SAR/kWh, is used. The overall cost of energy may be determined by aggregating the expenses associated with imported, exported, and consumed power, as expressed in equation (18):

$$C_{Net} = C_{Grid} + C_{Hybrid} + C_{Export} \tag{18}$$

In order to assess the true value of RES, it is essential to compare the cost of energy in a base case scenario (referred to as $C_{\text{Base Demand}}$) with the net cost benefit derived from imported, exported, and generated electricity (referred to as C_{Net}). This analysis is nece–ssary to comprehend the extent of the advantages obtained through the utilization of various energy sources in combination. Additionally, it enables the determination of the optimal allocation of wind and solar resources based on the supply profile. So, the hybrid power cost benefit is obtained from the follo–wing equation:

$$C_{HybridBenefit} = C_{Net} - C_{BaseDemand} \tag{19}$$

Table 10 summarizes the monthly breakdown of costs and cost benefits associated with the power demand for the GHP. Based on the power supply profile, the annual net cost benefit derived from hybrid RES amounts to around \$30.6 million. This number may be further augmented by lowering reliance on the grid to meet energy demands. The net cost varied between 16.28 and 18.13 \$Millions/month corres–ponding to February and January months while the base case cost remained between 18.44 and 20.39 \$Millions/month (Table 10).

Table 10. Monthly net cost benefit from Hybrid System (USD Millions/month)

Parameter	Net Electricity Cost	Base Case Electricity Cost	Net cost Benefit from Hybrid Sys
Month	C_{Net}	$C_{Base\ Demand}$	$C_{Hybrid\ Benefit}$
Jan	**18.13**	**20.39**	**2.26**
Feb	**16.28**	**18.44**	**2.16**
Mar	**17.90**	**20.39**	**2.49**
Apr	**17.35**	**19.73**	**2.38**
May	**17.62**	**20.39**	**2.77**
Jun	**16.97**	**19.73**	**2.76**
Jul	**17.59**	**20.39**	**2.79**
Aug	**17.51**	**20.39**	**2.87**
Sep	**17.10**	**19.73**	**2.63**
Oct	**17.74**	**20.39**	**2.65**
Nov	**17.39**	**19.73**	**2.34**
Dec	**17.83**	**20.36**	**2.53**
Year	**209.41**	**240.04**	**30.63**

6.3 Net Billing Case Economic Analysis

In a Net Billing structure, renewable energy systems have the ability to sell any surplus energy to the grid, often during peak periods at predetermined wholesale price (Feed-in Tariff). Consequently, the GHP pays the whole retail fee per kWh while using energy from the grid, and RE farms get the wholesale price from utility companies when electricity is sold back to the grid. Net billing tariff, T_{NB}, can be obtained by the following formula:

$$T_{NB} = \frac{C_{Net}}{E_{WT} + E_{PV} + E_{NET}} \qquad (20)$$

6.4 Net Metering (NM) Case Economic Analysis

In general, net metering credits are equivalent to the grid energy rates paid by the consumer. In the case of net metering, they can be carried over from one month to another and correspond to the tariff rate of the grid operator. In this arrangement, the price of one kWh of energy generated by RES is equivalent to that of a kWh of energy from the grid. The implementation of the NM system simplifies the calculation of energy cons–umption on the GHP bill because it accounts for the net energy usage only. The following equation illustrates the calculation of the net electricity tariff (T_{NM}) for GHP considering the net metering mechanism:

$$T_{NM} = \frac{(E_{WT}+E_{PV})\times T_{hybrid} + E_{GridNet}\times T_{Grid} - E_{RENet}\times T_{feed-in}}{E_{WT}+E_{PV}+E_{GridNet}+E_{RENET}} \qquad (21)$$

6.5 Net Metering with a Cap Case

Net metering mechanisms are used in some nations worldwide, giving the Billing Authority the discretion to permit the accumulation of surplus credits from one billing period to the next. Nevertheless, it is possible to use transfer energy credit within a span of 12 months. At the conclusion of the fiscal year, the Compensated Net Energy Export is limited to the aggregate quantity of energy imported from the grid. Consequently, any surplus energy will not be subject to compensation.

$$T_{NM\,CAP} = \frac{(E_{WT} + E_{PV})\times T_{hybrid} + E_{GridNet}\times T_{Grid}}{E_{WT} + E_{PV} + E_{GridNet} - E_{RENet}} \qquad (22)$$

7. RESULTS AND DISCUSSIONS

For a hybrid renewable energy system, it is important to find the optimum share between wind and solar that gives the system the lowest tariff. The trend for a tariff against PV share was obtained for all three scenarios, and the results are as follows:

- For net billing scenario, the range for adjusted tariff was between 39.96 and 46.8 \$/MWh, where the least tariff was achieved at 20% solar and 80% wind share, as shown in Figure 9. This is due to the fact that with high share of solar PV energy, the system will import more energy from the grid at higher tariff rate and will inject more energy into grid at low feed-in tariff rates.
- The net metering scenario has the least adjusted tariff of 26.5 \$/MWh when solar share is maximized. This is due to the fact that the feed-in tariff is equal to grid tariff and energy values injected and imported to and from the grid are the same. The optimum share, as shown in Figure 10, is observed at 100% solar and 0%.
- The net metering system with a compensation cap showed the same trend as in the previous scenario. The optimum share is obtained at 100% solar with 26.49 \$/MWh tariff, Figure 11.

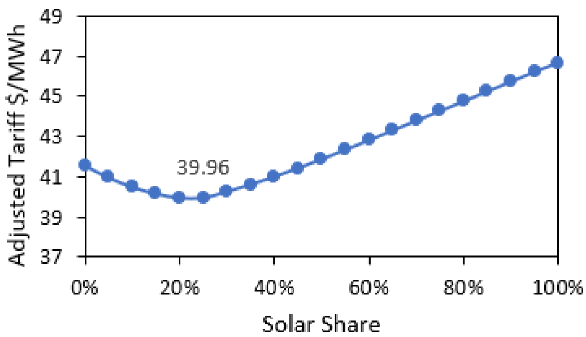

Figure 9. Net billing adjusted tariff against solar share

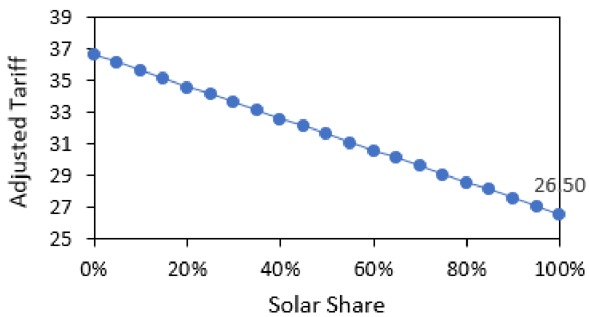

Figure 10. Net metering adjusted tariff against solar share

Table 11 summarizes all three cases and provide the optimum share for each case. The highest LCOH is ob–tained in net billing case with 2.33 \$/kg of hydrogen which is still lower than the grid tariff value of 2.72 \$/kg.

In contrast, the Net Metering option resulted in minimum LCOH of 1.65 $/kg with a LCOE of 26.49 $/MWh.

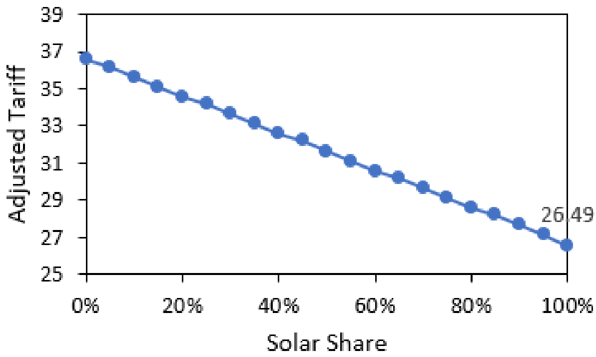

Figure 11. Net metering with cap-adjusted tariff against solar share

Table 11: Summary of different compensation scenarios

Case	System Share Solar Vs Wind	Tariff	LCOH
Units	%	$/MWh	$/kg
Case #1: Net Billing	20% Vs 80%	39.95	2.33
Case #2: Net Metering	100% Vs 0%	26.49	1.65
Case #3: Net Metering with Cap	100% Vs 0%	26.50	1.66

8. CONCLUSIONS

A feasibility study was conducted for the production of a green hydrogen plant using an electrolysis process powered through grid-connected PV and wind power. The analysis was carried out based on energy compensation standards, including net billing, net metering, and net metering system with injection cap. The optimum share of solar/wind energy contribution was found to be 20%/80% due to the intermittent nature of renewable sources. In contrast, the values of energy imported and exported from and to the grid were the same in the case of net metering case, which resulted in lower tariffs and LCOH.

In almost all scenarios, net metering proved advantageous with higher solar PV capacity. Consequently, GHP is required to pay a somewhat higher amount to access energy from the grid.

9. RECOMMENDATIONS

As the Kingdom of Saudi Arabia's plan includes higher penetration of renewables into the existing energy portfolio, the following recommendations could accelerate/help achieve the set targets:

- May adopt a motivative energy compensation system in order to encourage individuals and private sector to contribute to the renewable energy generation. This could be achieved by adopting the net energy metering or net energy billing system with relatively higher feed-in tariff.
- Consolidation (robust and smart) of the transmission system and the distribution network can help accommodate the higher penetration of renewable-based energy generation.
- The introduction of a CO_2 credit incentive will encourage investors, developers, and individuals to utilize renewable energy.

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NOMENCLATURE

AC	Alternating Current
AEC	Alkaline Electrolysis Cell
AEP	Actual Energy Production
AEY	Annual Energy Yield
CCUS	Carbon Capture, Utilization, and Storage
COE	Cost of Energy
COP	Climate Change Conference
DC	Direct Current
GH	Green Hydrogen
GHG	Greenhouse Gases
GHP	Green Hydrogen Plant
GSI	Global Horizontal Irradiance
HRH	His Royal Highness
kW	Kilowatt
kWh	Kilowatt Hour
kT	Kiloton
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
MW	Megawatt
MWh	Megawatt Hour
NPC	Net Present Cost

O & M	Operations and Maintenance
PCF	Plant Capacity Factor
RE	Renewable Energy
RES	Renewable Energy Sources
PV	Photovoltaic
SASO	Saudi Standards, Metrology, and Quality Organization
SGI	Saudi Green Initiative
WERA	Water and Electricity Regulatory Authority
WPD	Wind Power Density

Greek symbols

ρ	Air Density (kg/m^3)
α	Wind Shear Factor

ТЕХНО-ЕКОНОМСКА АНАЛИЗА ХИБРИДНОГ ЕЛЕКТРОЕНЕРГЕТСКОГ СИСТЕМА ВЕТРА/СОЛАРА ЗА ОБЕЗБЕЂИВАЊЕ ЕЛЕКТРИЧНЕ ЕНЕРГИЈЕ ЗА ПРОИЗВОДЊУ ЗЕЛЕНОГ ВОДОНИКА

А. Хомеида, О. Алгруни, Ш. Рехман, З. Анвар

Зелени водоник (ГХ) је препознат као основни стуб у обликовању одрживе глобалне будућности. Процес укључује хидролизу воде са одрживим изворима електричне енергије. Овај рад представља техно-економску процену хибридних обновљивих система за енергију ветра и соларне енергије у Јанбуу, Саудијска Арабија, како би се обезбедила чиста енергија за побољшање петрохемијских операција угљеника. Имплементација Политике компензације енергије, као што су нето мерење енергије или механизми нето наплате енергије, има значајан утицај на финансијску одрживост ГХ фабрике. Ово истраживање упоредило је утицај таквог механизма на нивелисану цену енергије (ЛЦОЕ) и нивелисану цену водоника (ЛЦОХ). Студија је препоручила усвајање Нето мјерног механизма као високо ефикасне стратегије за подстицање улагања приватног сектора у производњу обновљиве енергије у Краљевини Саудијској Арабији (КСА). Утврђено је да је овај приступ ефикасан, што је резултирало акумулираном тарифом за електричну енергију од 26,5 $/МВх и нивелисаним трошковима водоника (ЛЦОХ) од 1,65 $/кг.