

Exergy and Energy Analysis of Hydrogen Production Using Electrolysis Process Powered by Wind and Solar Energy

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Abstract - This study examines hydrogen production using a hybrid renewable energy system combining wind and solar energy sources. The experiment was conducted over four days, with data collected from 9:00 AM to 3:00 PM each day, focusing on solar irradiance, wind speed, and the energy and exergy efficiencies of each component—wind turbine, photovoltaic (PV) panel, and electrolyzer. Solar irradiance varied across the days, peaking at 160 W/m² but experiencing fluctuations due to weather conditions, while wind speeds ranged between 0 and 6 m/s, with the highest consistency observed on Day 3.

Each component's performance was measured by energy and exergy efficiency metrics, which revealed significant differences across the four days. The turbine's energy efficiency ranged from 3.83% to 8.24%, with exergy efficiency slightly lower, indicating mechanical and aerodynamic losses. Solar panel energy efficiency varied from 13.42% to 22.92%, impacted by irradiance stability, while the electrolyzer consistently showed high energy efficiency, between 59.06% and 63.42%, with exergy efficiency slightly lower. Total system efficiency ranged from 43.09% to 65.30% for energy and 24.23% to 35.35% for exergy.

Hydrogen production peaked on Day 1 and Day 2, reaching approximately 6000 mL, due to either stable solar or moderate wind input. Day 3, despite optimal wind speeds, produced slightly less hydrogen (5800 mL) due to limited solar input. Production on Day 4 was lowest (5000 mL), affected by high variability in both wind and solar conditions.

The results demonstrate that stable solar and wind inputs are essential for maximizing hydrogen production. High variability in energy inputs leads to reduced efficiency, highlighting the importance of reliable renewable sources or energy storage solutions. Future work could focus on optimizing the exergy efficiency of each component to further improve hydrogen production

and reduce energy losses, making the system more resilient and efficient for sustainable energy applications.

Keywords: Hydrogen production, Electrolysis efficiency, Renewable energy, Wind energy, Solar energy.

I. INTRODUCTION

The global energy crisis and climate change have accelerated the search for sustainable energy alternatives. Hydrogen, with its high energy density and zero emissions when burned, is a promising candidate to replace fossil fuels. Hydrogen production via water electrolysis, powered by renewable energy sources like wind and solar, offers a cleaner energy pathway.

Hydrogen serves as an "energy carrier" and can be stored for later conversion into electricity through fuel cells. Its applications are diverse, from transportation (hydrogen-powered vehicles) to industry (chemical processes). Additionally, hydrogen can address renewable energy intermittency, storing excess electricity for later use.

Electrolysis splits water into hydrogen and oxygen using electricity. This process is represented as: $2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$. Wind and solar energy, abundant and increasingly cost-effective, are ideal renewable energy sources for electrolysis. Combining these sources with electrolysis can sustainably produce hydrogen and reduce dependence on fossil fuels.

Exergy analysis evaluates process efficiency by accounting for energy quality. It measures a system's potential to perform useful work. Exergy cannot be created or destroyed, but it can be lost through inefficiencies, which can be identified and minimized through analysis.

Recent studies highlight hydrogen production through renewable energy as a pathway to decarbonization. Solar-powered electrolysis performance depends on solar irradiance, and wind-driven systems vary with wind speed. Exergy analysis provides a deeper understanding of inefficiencies,

emphasizing the need for system optimization to reduce losses.

Newer electrolyzer technologies, like proton exchange membrane (PEM) electrolyzers, outperform traditional alkaline electrolyzers. However, scaling up these systems for industrial use requires significant investment and technological improvements [1].

In summary, while renewable energy-powered electrolysis is viable, challenges remain. Optimizing energy and exergy efficiencies, improving electrolyzer designs, and mitigating renewable energy intermittency are key areas for further research and development.

This research aims to calculate the overall exergy efficiency of hydrogen production, identify major exergy losses, and provide recommendations for system efficiency improvements.

II. THEORIES AND EXPERIMENTAL SETUP

2.1 Theories

Exergy analysis is a method that combines mass and energy conservation with the second law of thermodynamics to evaluate, design, and optimize energy systems. Exergy measures the maximum work a system or energy flow can produce when reaching equilibrium with a reference environment. It quantifies the system's potential for change due to its deviation from stable equilibrium. Unlike energy, exergy is not conserved, but is consumed or destroyed by irreversibilities in real processes. The amount of exergy consumed during a process is directly related to the entropy generated by those irreversibilities [2].

Exergy analysis is valuable for enhancing energy resource efficiency by identifying the locations, types, and amounts of waste and losses. Compared to energy analysis, exergy analysis offers more meaningful efficiencies, as it directly measures how closely a process approaches ideal performance. Therefore, exergy analysis precisely pinpoints opportunities to design more efficient energy systems by minimizing inefficiencies. Many engineers and scientists advocate for exergy analysis to assess thermodynamic performance, as it provides deeper insights and is more effective in guiding efficiency improvement efforts than energy analysis [2].

Exergy analysis requires specifying the characteristics of a reference environment, typically its temperature, pressure, and chemical composition. The results of exergy analysis are relative to this reference, often modeled after the local environment. A system's exergy is zero when it is in

equilibrium with the reference environment—a state known as the dead state. In this state, the system is in mechanical (pressure), thermal (temperature), and chemical (chemical potential) equilibrium with its surroundings. Additionally, the system has no relative motion or elevation. Under these conditions, no spontaneous change can occur within the system or the environment, nor can any interaction take place between them. The exergy is zero.

The efficiency of a wind turbine is the ratio of its output power to the input wind energy. Exergy efficiency is calculated by dividing the useful exergy produced by the turbine by the total exergy of the airflow. These concepts are illustrated in the following equations [2,3,4].

$$\eta_{WT} = \frac{P_{WT}}{\frac{1}{2} \times \rho_{air} \times A_{WT} \times V_1^3} \quad (1)$$

$$Ex_{WT} = \dot{m}_{air} (\Delta ex_{ki} + \Delta ex_{po} + \Delta ex_{ph,in} + \Delta ex_{ch}) \quad (2)$$

$$e_{ki,1} = \frac{1}{2} V_1^2 \quad (3)$$

$$e_{ki,2} = \frac{1}{18} V_1^2 \quad (4)$$

$$P_1 = P_o + \frac{1}{2} V_1^2 \quad (5)$$

$$P_2 = P_o - \frac{1}{18} V_1^2 \quad (6)$$

$$e_{ph,1} = (C_{p,a} + \omega C_{p,v}) T_o \left[\frac{T_1}{T_o} - \ln \left(\frac{T_1}{T_o} \right) \right] + (1 + 1.6078\omega) R T_o \left(\frac{P_1}{P_o} \right) \quad (7)$$

$$e_{ph,2} = (C_{p,a} + \omega C_{p,v}) T_o \left[\frac{T_2}{T_o} - \ln \left(\frac{T_2}{T_o} \right) \right] + (1 + 1.6078\omega) R T_o \left(\frac{P_2}{P_o} \right) \quad (8)$$

$$\dot{m}_{air} = \frac{2}{3} \times \rho_{air} \times A_{WT} \times V_1 \quad (9)$$

$$\psi_{WT} = \frac{P_{WT}}{Ex_{WT}} \quad (10)$$

In the equations, ρ_{air} represents air density (kg/m^3), R is the gas constant ($\text{J/kg}\cdot\text{K}$), A_{WT} is the wind turbine area (m^2), Ex_{WT} is the total exergy of wind turbine (J/s), and ex_{ki} , ex_{po} , $ex_{ph,in}$, ex_{ch} , and e_{ki} are the specific kinetic exergy, specific potential exergy, specific physical exergy, specific chemical exergy and kinetic energy, respectively (J/kg). Δex denotes the change in specific exergy (J/kg) between the inlet and outlet. P_{WT} , P , V , ω , $C_{p,a}$, $C_{p,v}$ and ψ_{WT} are the wind turbine power (J/s), wind power (J/s), wind velocity (m/s), absolute humidity ($\text{kg water/kg dry air}$), air specific heat ($\text{J/kg}^\circ\text{C}$), vapor specific heat ($\text{J/kg}^\circ\text{C}$), and exergy efficiency, respectively. P_o and T_o are the standard atmospheric pressure and temperature, 1 atm and 288.15 K, respectively. The subscript 'i' indicates inlet or outlet conditions. For the overall exergy calculation, chemical and potential exergy terms are disregarded.

The efficiency and exergy of an electrolyzer are calculated using the following equations, based on the following assumptions [2,3,4]:

1. Only electrical power input is considered as exergy input.
2. Water's exergy and oxygen exergy are not included in the electrolyzer's exergy analysis.
3. Kinetic and potential energy of reactants and products are neglected.

$$\eta_{e,EZ} = \frac{\dot{m}_{H_2} HHV_{H_2}}{\text{Electrolyzer input electric energy}} \quad (11)$$

$$\psi_{EZ} = \frac{\dot{m}_{H_2} \left(ex_{ch} + C_{p,H_2} T_o \left[\frac{T}{T_o} - 1 - \ln \left(\frac{T}{T_o} \right) + \left(\frac{p_{H_2}}{p_o} \right)^{\frac{\phi}{\phi-1}} \right] \right)}{\text{Electrolyzer input electric energy}} \quad (12)$$

In the equations, \dot{m}_{H_2} represents the hydrogen mass flow rate (kg/s), HHV denotes the hydrogen higher heating value, ϕ is assumed to be 1.4, C_{p,H_2} is 14.890 kJ/kg·K, and ex_{ch} represents the chemical energy and exergy (117,113 kJ/kg).

A PV panel's energy consists of two primary components: electrical and thermal energy. Solar radiation heats the panel during electricity generation, producing thermal energy that is typically considered waste due to its dissipation to the environment. Traditionally, PV panel efficiency is calculated as the ratio of generated electricity to solar irradiation, neglecting heat loss. However, an exergy balance of the PV panel can be expressed as follows [2,3]:

$$\dot{E}X_{s,in} - \dot{E}X_{s,out,usf} - \dot{E}X_{s,loss} - \dot{E}X_{s,dest} = 0 \quad (13)$$

In the equation, $\dot{E}X_{s,in}$, in represents the exergy input, $\dot{E}X_{s,out,usf}$ is the net useful exergy output, $\dot{E}X_{s,loss}$, loss is the exergy loss, and $\dot{E}X_{s,dest}$, dest is the exergy destruction rate of the PV panels. The exergy input of the PV panels can be calculated using the following equation [2,3]:

$$\dot{E}X_{s,in} = S_T A_{PV} \left[1 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun}} \right) + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}} \right)^4 \right] \quad (14)$$

In the equation, A_{PV} represents the PV panel area, S_T is the solar irradiation on the PV panels, T_{amb} is the ambient air temperature, and T_{sun} is the sun temperature, assumed to be 6000 K [2]

The net useful exergy output can be calculated using the following equation:

$$\dot{E}X_{s,out,usf} = V_m I_m \quad (15)$$

In the equation, V_m represents the maximum voltage and I_m is the maximum current of the PV panels. These parameters are typically found in manufacturer data sheets. The exergy loss can be calculated using the following equation [2]:

$$\dot{E}X_{s,loss} = \dot{Q}_{s,loss} \left(1 - \frac{T_{amb}}{T_{PV}} \right) \quad (16)$$

$\dot{Q}_{s,loss}$ represents the heat loss rate, calculated using the following equation [2]:

$$\dot{Q}_{s,loss} = h_c A_{PV} (T_{PV} - T_{amb}) \quad (17)$$

In the equation, h_c represents the convective heat transfer coefficient from PV panels to the ambient, calculated using the following equation [2]:

$$h_c = 2.8 + 3V_w \quad (18)$$

In the equation, V_w represents the wind velocity. The exergy destruction rate of the PV panels is given by the following equation[2,3]:

$$\dot{E}X_{s,dest} = \dot{E}X_{s,in} - \dot{E}X_{s,out,usf} - \dot{E}X_{s,loss} \quad (19)$$

The exergy efficiency of the PV panels is calculated using [2,3]:

$$\psi_s = \frac{\dot{E}X_{s,out,usf}}{\dot{E}X_{s,in}} \quad (20)$$

2.2 Experimental Setup

This study employed an alkaline water electrolysis system with SS316L stainless steel electrodes, following a previous study by El Soly [8] that compared dry and wet cell electrolysis using the same material. Olivares [19] also used SS316 material in his research on hydrogen evolution during electrolysis. The electrodes were flat plates. The electrolyzer dimensions are provided in Table 2.1, and the circuit diagram is shown in Figure 2.1 [5].

Table 2.1: Electrolyzer Specification [5]

Specification	Value
Cell volume	1,4 L
Electrode dimension	70 x 70 x 1,5 mm
Amount of electrode	10
Electrode material	SS316
Electrolyte	NaOH
Electrolyte concentration	25% wt

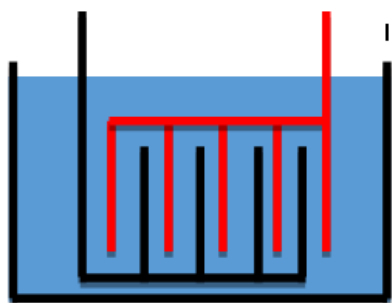


Figure 2.1: Electrolyzer schematic [5]

The detailed specifications of the turbine and solar panels are provided in Figure 2.2, Table 2.2, Table 2.3, and Figure 2.3. The experimental setup is illustrated in Figure 2.4 [5].

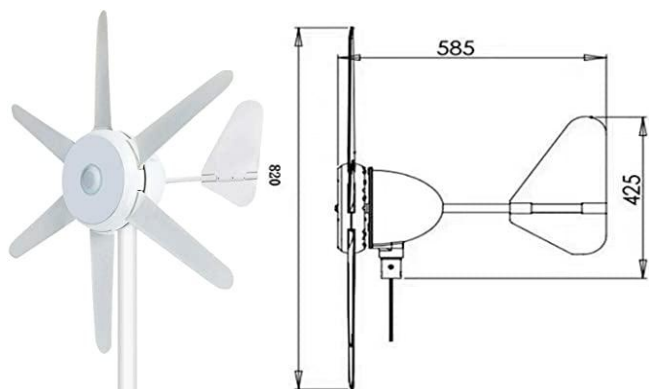


Figure 2.2: Wind Turbine [5]

Table 2.2: Wind Turbine Specification [5]

Specification	Value
Blade	6
Starting wind speed	1 m/s
Rated wind speed	12 m/s
Output Voltage	12V
Maximum Power	300W

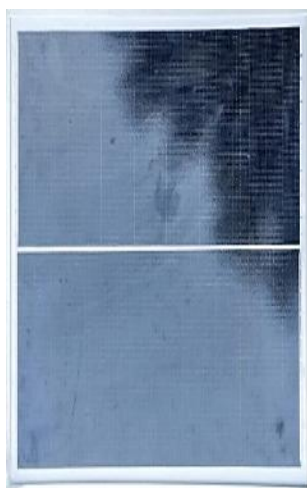


Figure 2.3: Solar Panel [5]

Table 2.3: Solar Panel Specification [5]

Specification	Value
Dimension	350 × 530 × 25 mm
Maximum Power point	30 W
Voltage at Pmax (V_{mp})	18.4 V
Current at Pmax (I_{mp})	2.72 A
Open-Circuit Voltage (V_{oc})	22.6 V
Short-Circuit Current	2.94 A

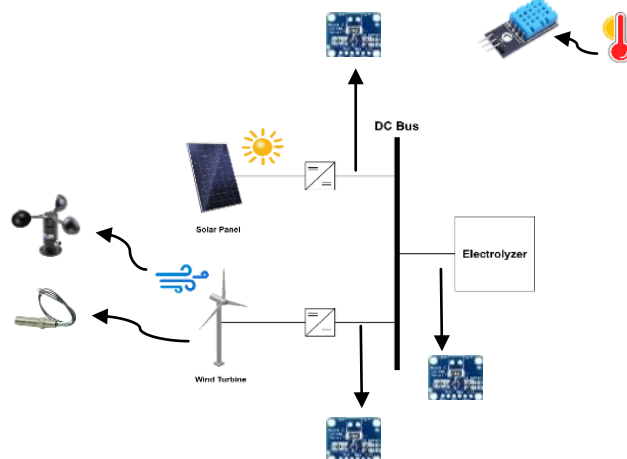


Figure 2.4: Experimental setup [5]

III. RESULTS AND DISCUSSIONS

An electrolysis experiment using a wind turbine and solar panel was conducted over four days, from 9:00 AM to 3:00 PM. The solar irradiation measurements are presented in Figure 3.1.

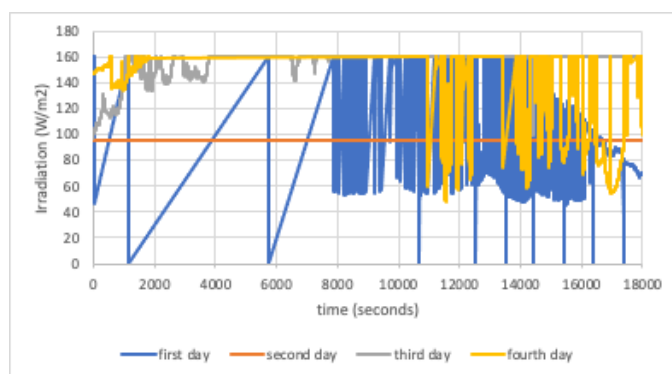


Figure 3.1: Plot of Solar Irradiance vs. Time

From Figure 3.1, the solar irradiation values fluctuate between approximately 0 W/m² and 160 W/m² across the four days. On the first day (blue), irradiation starts near 0 W/m² and peaks at around 150 W/m² before experiencing sharp drops and rises. The second day (orange) shows more stable irradiation at roughly 100 W/m² throughout the measurement period. The third day (gray) remains fairly constant, close to 130 W/m². On the fourth day (yellow), irradiation peaks at approximately 160 W/m².

around 160 W/m² but fluctuates significantly, dropping to almost 0 W/m² at various points. These large fluctuations indicate potential cloud cover or other shading effects during the measurement.

Based on Figure 3.2, the wind speed data from 9 AM to 3 PM over four days, there are noticeable fluctuations and trends. The wind speeds generally range between 0 and 6 m/s across all days.

On the first day (blue), the wind speed shows moderate variation, ranging between 1 and 5 m/s, with occasional peaks reaching around 5 m/s. The second day (orange) exhibits lower wind speeds overall, fluctuating mostly between 0 and 3 m/s, with a few peaks reaching above 4 m/s but remaining generally calmer compared to the first day. The third day (gray) demonstrates higher wind speeds, staying consistently between 2 and 5 m/s for most of the time and peaking near 6 m/s on multiple occasions. This day appears to have the strongest and most consistent wind patterns. The fourth day (yellow) displays more variability, with wind speeds fluctuating sharply between 1 and 5 m/s, indicating intermittent gusts throughout the measurement period.

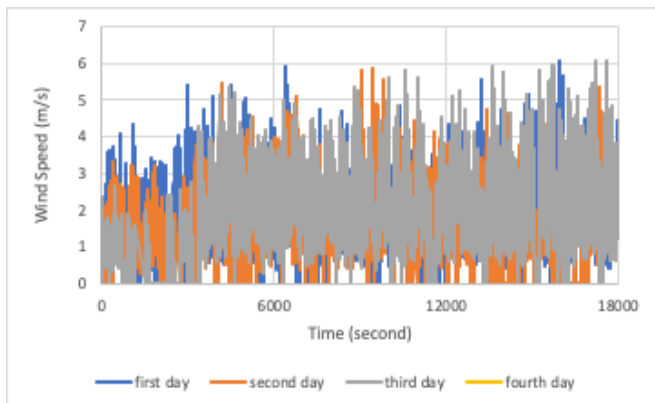


Figure 3.2: Plot of Wind Speed vs. Time

Quantitatively, the third day experienced the highest and most stable wind speeds, which would be ideal for wind energy generation. The second day had the lowest wind speeds, with frequent drops below 1 m/s, making it less favorable for any wind-related applications. The overall pattern shows that wind speeds vary day by day, likely influenced by weather patterns or topographical factors that affect airflow during the measurement period.

The graph 3.3 showing cumulative hydrogen (H₂) production over four days reflects the combined performance of wind turbines and solar PV systems from 9 AM to 3 PM, where production is measured in milliliters. The data from wind speed and solar irradiation you provided earlier can be used to understand the variations in hydrogen output.

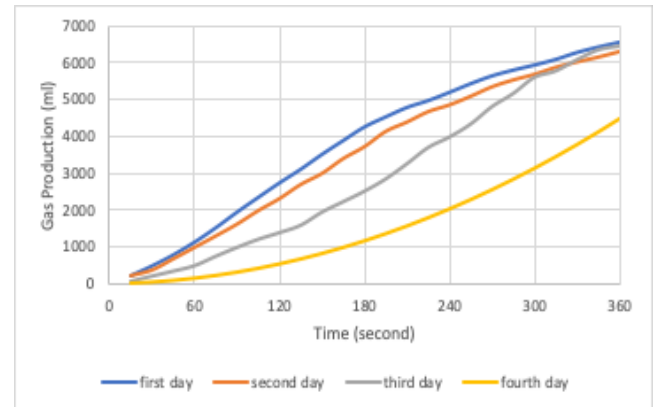


Figure 3.3: Plot of Hydrogen Production vs. Time

On the first day (blue), hydrogen production reached nearly 6000 mL by the end of the measurement period. Wind speeds were moderate, fluctuating between 1 and 5 m/s, and solar irradiation was unstable, peaking around 150 W/m² with significant dips. Despite the variability in both wind and solar input, the system achieved relatively high hydrogen production, suggesting that sufficient renewable energy was available for electrolysis.

On the second day (orange), production also neared 6000 mL, but slightly lower than the first day. Wind speeds were lower, fluctuating mostly between 0 and 3 m/s, and solar irradiation was quite stable around 100 W/m². The steady solar input likely contributed to consistent hydrogen production, despite the lower wind speeds.

On the third day (gray), cumulative hydrogen production reached around 5800 mL. This day had the highest wind speeds, ranging between 2 and 6 m/s, and relatively stable solar irradiation around 130 W/m². The higher wind speeds provided more energy, but hydrogen production was only marginally less than the first two days, likely due to the limitations of the solar component.

The fourth day (yellow) shows significantly lower hydrogen production, reaching only about 5000 mL. Wind speeds fluctuated between 1 and 5 m/s, but solar irradiation was highly erratic, peaking at 160 W/m² but with frequent drops to near 0 W/m². The large variations in solar input, combined with moderate wind speeds, likely led to this lower hydrogen output.

In summary, the highest hydrogen production occurred on days with either stable solar input (second day) or a combination of moderate wind and solar energy (first day). The fourth day's low and erratic solar irradiation significantly hindered hydrogen production, despite reasonable wind speeds. This suggests that consistent solar input is critical for maximizing hydrogen production in the system.

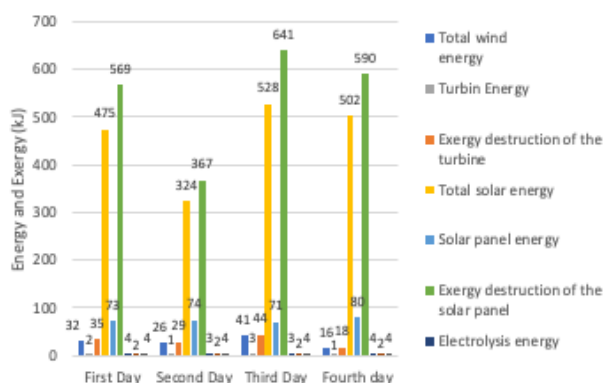


Figure 3.4: Plot of Energy and Exergy vs. Time

The graph 3.4 illustrates the energy and exergy distribution across four days in your hydrogen production experiment, utilizing both wind turbines and solar PV systems. The bars represent various energy and exergy components, providing insight into the system's performance and efficiency.

Day-by-Day Energy and Exergy Analysis

Day 1:

Wind Energy System: Total wind energy input was 31,567.63 kJ, with the wind turbine capturing 1,549.16 kJ. The exergy destruction in the turbine was relatively high, indicating a loss of potential work.

Solar Energy System: Solar energy input was substantial, at 474,531 kJ, with the panel capturing 72,576.15 kJ. Exergy destruction was 568,922.96 kJ, showing that while solar input was high, inefficiencies within the system led to a large loss of usable work potential.

Electrolysis Process: The electrolysis unit consumed 3,543.82 kJ and generated 2,247.34 kJ of hydrogen energy. Exergy destruction for electrolysis was 3,610.73 kJ, indicating room for improvement in the conversion efficiency of the electrolysis process.

Day 2:

Wind Energy System: Total wind energy was 25,726.25 kJ, with the turbine capturing 986.31 kJ, lower than on Day 1. The exergy destruction also reduced, following the decline in total wind energy.

Solar Energy System: Solar input was 324,268.08 kJ, while panel output was 74,330.77 kJ, slightly higher than Day 1. Exergy destruction decreased to 367,480.10 kJ, but remained significant.

Electrolysis Process: Energy for electrolysis was 3,318.64 kJ, with hydrogen production at 1,976.10 kJ. Exergy destruction in electrolysis slightly reduced, showing a minor increase in conversion efficiency.

Day 3:

Wind Energy System: Total wind energy peaked at 41,179.39 kJ, with turbine energy output rising to 3,392.44 kJ. Exergy destruction also increased due to the higher input energy, indicating higher losses associated with increased wind energy input.

Solar Energy System: Solar input rose again to 528,065.58 kJ, but solar panel output dropped to 70,868.34 kJ. Exergy destruction, however, spiked to 641,466.63 kJ, implying inefficiencies due to the large energy input.

Electrolysis Process: With 3,444.79 kJ used in electrolysis and hydrogen production reaching 2,034.58 kJ, exergy destruction was slightly lower, suggesting improved performance within this subsystem.

Day 4:

Wind Energy System: Wind input dropped significantly to 16,337.76 kJ, with the turbine output reducing to 725.71 kJ. This lower energy availability led to a decrease in exergy destruction.

Solar Energy System: Solar input remained high at 501,847.65 kJ, with panel output increasing to 79,598.37 kJ. Exergy destruction slightly reduced to 589,504.51 kJ but remained high, revealing consistent inefficiencies in solar energy conversion.

Electrolysis Process: With the highest energy input of 3,732.49 kJ, electrolysis achieved an energy output of 2,282.93 kJ in hydrogen. Exergy destruction was the highest at 3,818.58 kJ, suggesting that high input levels may lead to higher irreversibilities within the system.

Comparative Analysis

The wind turbine's performance varied over four days, with energy capture and exergy destruction linked to wind availability. Higher wind input, as on Day 3, led to increased output but also higher exergy destruction, revealing mechanical inefficiencies. Solar panels, while receiving high solar energy (particularly on Days 1, 3, and 4), showed significant exergy losses due to photovoltaic inefficiencies. Day 4 achieved the best efficiency due to stable sunlight. The electrolysis unit maintained stable energy use and exergy loss; minor efficiency gains on Days 3 and 4 suggest that

optimizing reaction conditions could further reduce these energy losses.

performance. This variation shows that optimal subsystem efficiencies are essential for balanced system performance.

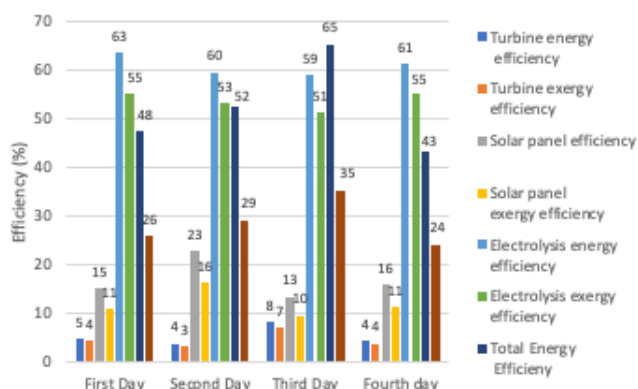


Figure 3.5: Plot of Energy and Exergy Efficiency vs. Time

The bar chart 3.5 displays the energy and exergy efficiency of various components over four consecutive days. Each color represents different efficiencies, including turbine energy and exergy efficiency (blue and orange), solar panel energy and exergy efficiency (gray and yellow), electrolysis energy and exergy efficiency (light blue and green), and total system energy and exergy efficiency (dark blue and brown).

Solar Panel Energy and Exergy Efficiency

Solar panel efficiencies vary notably over the four days. Day 1 shows an energy efficiency of 15.29% and an exergy efficiency of 10.96%, suggesting thermal inefficiencies and material constraints in photovoltaic conversion. On Day 2, energy efficiency increases to 22.92% with exergy efficiency at 16.42%, likely due to improved irradiance. Day 3 sees a decrease to 13.42% (energy) and 9.61% (exergy), possibly due to environmental factors like cloud cover. Day 4 shows slightly improved solar efficiency at 15.86% (energy) and 11.38% (exergy), indicating moderate thermal losses and inefficiencies in capturing solar irradiance.

Electrolysis Energy and Exergy Efficiency

The electrolysis unit consistently shows high energy efficiency, between 59.06% and 63.42%, and exergy efficiency between 51.23% and 55.07%. This suggests a stable hydrogen production process with minor exergy losses. On Day 4, electrolysis efficiency reaches its peak, likely due to favorable reaction conditions.

Overall System Efficiency

Total energy efficiency for the system varies from 43.09% to 65.30%, while exergy efficiency ranges from 24.23% to 35.35%. The highest overall efficiency appears on Day 3, aligning with peak turbine and stable electrolysis

Comparative Analysis

Wind Turbine: With the lowest efficiency among components (energy efficiency from 3.83% to 8.24% and exergy efficiency from 3.34% to 7.18%), the turbine shows substantial losses, likely due to mechanical inefficiencies and wind fluctuations. Enhancing aerodynamic design and implementing variable-speed operation could improve efficiency.

Solar Panel: Solar efficiency is higher than that of the turbine, ranging from 13.42% to 22.92% in energy and 9.61% to 16.42% in exergy. Improving photovoltaic materials, employing cooling solutions, and using solar tracking technology may help reduce energy losses.

Electrolysis Unit: With consistently high efficiencies, the electrolysis unit effectively converts electrical energy into hydrogen, though optimizing catalysts and electrode materials could further reduce exergy losses.

Efficiency Improvement Strategies

Enhancing the system's efficiency involves variable-speed turbines, optimized blades, multi-junction solar cells with cooling, and advanced electrolysis catalysts. A centralized control system can stabilize power distribution. Improving wind capture, solar materials, and electrolysis efficiency could increase energy and exergy performance, creating a more sustainable solution.

IV. CONCLUSION

This experiment involved evaluating hydrogen production from renewable energy sources (wind and solar) over four days, with data collected from 9:00 AM to 3:00 PM each day. The parameters measured included solar irradiance, wind speed, energy and exergy efficiencies of each component (turbine, photovoltaic panel, and electrolyzer), and the total system efficiency. Here's a breakdown of the findings for each parameter:

1. Solar Irradiance:

Solar energy varied widely across the four days, with fluctuations attributed to cloud cover and changing weather conditions.

On Day 1, irradiance reached approximately 150 W/m², but showed significant fluctuations.

Day 2 had stable solar input around 100 W/m^2 , providing consistent energy for the solar panel.

Day 3 experienced moderate irradiance around 130 W/m^2 .

Day 4 saw the highest peaks at 160 W/m^2 but with substantial drops, which reduced the effectiveness of solar energy conversion.

2. Wind Speed:

Wind energy availability was inconsistent, affecting the turbine's performance daily.

Day 1 had moderate wind speeds, ranging from 1 to 5 m/s.

Day 2 had the lowest wind speeds (0-3 m/s), limiting the turbine's energy production.

Day 3 had the highest and most stable wind speeds (2-6 m/s), optimal for energy generation.

Day 4 exhibited sharp fluctuations between 1 and 5 m/s, reducing the system's ability to maintain a consistent energy flow.

3. Component Efficiencies:

Wind Turbine: The turbine's energy efficiency ranged from 3.83% to 8.24% across the four days, with exergy efficiency between 3.34% and 7.18%. The highest efficiency was observed on Day 3, when wind speeds were most favorable.

Solar Panel: The solar panel's energy efficiency fluctuated from 13.42% to 22.92%, while exergy efficiency ranged between 9.61% and 16.42%. Day 2 had the highest solar efficiency due to stable irradiance, but days with fluctuating irradiance (Day 1 and Day 4) showed reduced efficiency.

Electrolyzer: Energy efficiency for hydrogen production through electrolysis was consistently high, ranging from 59.06% to 63.42%, while exergy efficiency was between 51.23% and 55.07%. The highest efficiency values were observed on Day 4, likely due to optimal energy conditions for the electrolysis process.

4. Total System Efficiency:

The total energy efficiency for the combined system ranged from 43.09% to 65.30% across the four days, with the highest recorded on Day 3 due to strong wind conditions.

Total exergy efficiency was lower, between 24.23% and 35.35%, reflecting energy losses due to irreversibilities and less-than-ideal conversion processes. Exergy efficiency peaked on Day 3, indicating the importance of stable wind and solar conditions for maximizing useful work potential.

5. Hydrogen Production:

Cumulative hydrogen production over the four days reached its peak on Day 1 and Day 2, nearing 6000 mL, attributed to either moderate wind or stable solar conditions. Production decreased slightly on Day 3 to about 5800 mL, despite high wind speeds, due to limited solar input. On Day 4, hydrogen production was lowest (around 5000 mL), likely due to the variability in solar irradiance and inconsistent wind speeds, underscoring the system's sensitivity to energy input stability.

Summary and Implications

Increasing system efficiency requires variable-speed turbines, optimized blades, multi-junction solar cells with cooling, and advanced electrolysis catalysts. A centralized control can stabilize power. Enhancing wind capture, solar materials, and electrolysis efficiency boosts energy and exergy performance for a more sustainable solution.

ACKNOWLEDGEMENT

The financial support by RKAT Grant Funding, Faculty of Engineering, Undip, Fiscal Year 2024 is acknowledged.

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Citation of this Article:

Faisal Rahman, Berkah Fajar T.K, Khoiri Rozi, & Crysmas. (2024). Exergy and Energy Analysis of Hydrogen Production Using Electrolysis Process Powered by Wind and Solar Energy. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 8(10), 238-246. Article DOI <https://doi.org/10.47001/IRJIET/2024.810033>
