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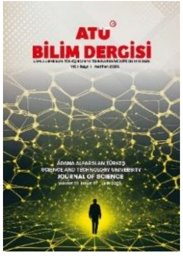

Seasonal analysis of solar energy and hydrogen production potential in Adana

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Abstract

This study focuses on evaluating the performance of a system comprising an 80W solar panel for electricity generation and hydrogen production via alkaline electrolysis, specifically designed for the Adana region. Simulations conducted in MATLAB/Simulink explored the effects of varying temperature and radiation levels on system performance. The findings reveal a direct correlation between power generation and solar radiation, with higher radiation levels leading to increased power output. However, elevated temperatures negatively impact the efficiency of the PV panel, resulting in reduced power generation. In the experimental setup, graphite (G) and silver-copper-modified graphite (Ag-Cu/G) electrodes were utilized as cathodes, while a platinum electrode served as the anode. Operating voltages ranging from 2.5V to 3V were applied, demonstrating that hydrogen production increases with higher operating voltages. Surface characterization of the electrodes was conducted using SEM-EDX analysis. At 3V, after 15 minutes of operation, hydrogen volumes of 15 mL and 21.4 mL were obtained for G and Ag-Cu/G electrodes, respectively. Seasonal variations were also considered, highlighting that spring's frequent rainy and cloudy conditions limit sunlight availability, whereas the extended clear-sky durations of summer months offer a significant advantage for hydrogen production.

Keywords: Electrocatalyst; Hydrogen; MATLAB/Simulink; PV

Adana ili güneş enerjisi ve hidrojen üretim potansiyelinin mevsimsel analizi

Öz

Bu çalışma, Adana bölgesi için 80W'lık bir güneş paneli kullanılarak elektrik üretimi ve alkali elektroliz yoluyla hidrojen üretimi gerçekleştiren bir sistemin performansını değerlendirmeye odaklanmaktadır. MATLAB/Simulink ortamında gerçekleştirilen simülasyonlar, sıcaklık ve ışınım seviyelerinin sistem performansı üzerindeki etkilerini incelemiştir. Bulgular, güç üretimi ile güneş ışınımı arasında doğrudan bir ilişki olduğunu göstermiştir; ışınım seviyesinin artması, PV panel tarafından üretilen gücü artırmaktadır. Ancak, sıcaklığın artması panel verimliliğini olumsuz etkileyerek üretilen gücün azalmasına yol açmaktadır. Deneysel çalışmada, katot olarak grafit (G) ve gümüş-bakır modifiye grafit (Ag-Cu/G) elektrotlar, anot olarak ise platin elektrot kullanılmıştır. 2,5V ile 3V arasında değişen çalışma voltajları uygulanmış ve hidrojen üretiminin çalışma voltajı arttıkça yükseldiği gözlemlenmiştir. Elektrotların yüzey karakterizasyonu SEM-EDX analizi ile gerçekleştirilmiştir. 3V uygulandığında, 15 dakikalık bir süre sonunda G ve Ag-Cu/G elektrotları için sırasıyla 15 mL ve 21,4 mL hidrojen hacimleri elde edilmiştir. Mevsimsel değişimler de değerlendirilmiştir, ilkbahar mevsimindeki sık yağmurlu ve bulutlu hava koşullarının güneş ışığına erişimi sınırladığı, buna karşın yaz aylarının uzun ve açık hava süreleri sayesinde hidrojen üretimi açısından önemli bir avantaj sunduğu belirlenmiştir.

Anahtar Kelimeler: Elektrokatalizör; Hidrojen; MATLAB/Simulink; PV

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1. Introduction

Adana, characterized by high solar radiation and extended daylight hours, especially during spring and summer, stands out as one of the most ideal southern provinces in Türkiye for solar energy investments. This region is well-suited for large-scale solar power harvesting due to its advantageous climate and geographic advantages. Adoption of solar energy could be very beneficial for Adana, as it would decrease dependence on fossil fuels by the country, lower current account deficit, and hence lighten the economic burden on households and businesses [1, 2]. Solar energy is a clean, renewable resource that can help prevent global climate change and align well with Türkiye's sustainable development objectives. Enhancing energy security and reducing dependency on external energy sources are two benefits of integrating solar energy into the country's overall energy sources [3, 4]. In this context, solar energy's role in enabling hydrogen production has a critical synergy in the transition toward sustainable energy systems. Hydrogen is a clean and sustainable energy carrier. In contrast to fossil fuels, its utilization in combustion reactions or fuel cells generates only water vapor, leading to zero carbon emissions. This characteristic represents a major advantage in terms of environmental sustainability [5, 6]. Its energy storage capability addresses the intermittent issues of renewable energy sources by balancing supply and demand, thus enhancing the flexibility of energy systems [7, 8]. Furthermore, hydrogen is widely utilized in sectors such as chemistry, industry, and transportation, highlighting its versatility as an energy source [5, 9]. For countries which are reliant on energy imports, producing hydrogen domestically can enhance energy security and support the transition toward energy independence. [10, 11]. Recent cost reductions and technological advancements have made hydrogen economically competitive, accelerating its integration into energy systems and positioning it as a key player in the transition from fossil fuels to clean energy [12]. The produced hydrogen can be currently used for energy storage, transport, and industrial application purposes, therefore making this system altogether versatile in dealing with energy in a sustainable manner [13].

This study highlights the feasibility of utilizing solar energy in Adana and its incorporation into a hybrid energy system for hydrogen production. This system receives converted electricity from solar PV panels to feed an alkali electrolysis unit to produce hydrogen [13, 14]. To evaluate the performance of the solar PV panels under the specific environmental conditions of Adana, simulations were conducted using MATLAB/Simulink. These simulations accounted for critical parameters such as solar radiation levels, ambient temperature, and panel efficiency, which are essential for optimizing hydrogen production [15, 16]. Research has shown that the efficiency of photovoltaic systems can be significantly affected by environmental factors, including temperature and irradiance [17, 18]. As solar irradiance increases, the number of photons absorbed by the solar panels also increases, leading to higher electricity generation. However, high temperatures negatively affect the efficiency of photovoltaic (PV) panels. This phenomenon is primarily due to the increasing energy losses in the semiconductor materials (typically silicon) used in PV panels as temperatures rise. At higher temperatures, the internal resistance of the PV panels increases, which in turn raises the recombination rate of electron-hole pairs. As a result, the open-circuit voltage (Voc) decreases, leading to a reduction in the overall efficiency of the panel. For instance, it has been established that the electrical efficiency of PV panels decreases with increasing temperature, emphasizing the need for effective thermal management strategies [19, 20]. By leveraging the region's favorable solar conditions, Türkiye can enhance its energy independence, reduce greenhouse gas emissions, and contribute to a more sustainable future [21, 22]. The study examines the seasonal usability of solar energy for hydrogen production in the Adana region, with a detailed analysis of the effects of temperature and solar radiation levels on this process. The importance of renewable energy sources in sustainable energy production is growing. In this context, evaluating regional potential and analyzing the hydrogen production process via electrolysis are critical for optimizing energy conversion efficiency. Understanding these factors can contribute to the development of more efficient and sustainable energy systems.

In this study, the integrated small-scale off-grid energy system fitted with an 80W solar photovoltaic panel constitutes the system configuration and provides the electricity supply to the electrolysis unit. The performance of the solar PV panel was simulated using MATLAB/Simulink to check the output for various sunlight and temperature conditions that are typical during both spring and summer months in Adana. Furthermore, different cathode materials were tested to optimize hydrogen production. The actual parameters considered in this study are radiation levels, ambient temperature, electrode efficiency and day duration to calculate the proper hydrogen production.

2. Methods

In this study, an off-grid 80W PV panel system was designed and simulated using MATLAB/Simulink to evaluate its performance in the Adana region during the spring and summer seasons of 2024 (Figure 1). The primary objective was to assess the impact of different climatic conditions on the electricity generated by the PV panel and its subsequent use in hydrogen production through alkaline electrolysis. The technical specifications of the solar PV panel used in the simulations are shown in Table 1.

Table 1. Solar PV panel specifications used in the proposed system

Parameter	Value
Maximum Power (Pmax)	80 W
Open Circuit Voltage (Voc)	21.6 V
Voltage at Maximum Power (Vmp)	17.8 V
Short Circuit Current (Isc)	5.2 A
Current at Maximum Power (Imp)	4.5 A
Number of Cells	36

The simulated solar PV system comprises an 80W monocrystalline solar panel, a charge controller, and a battery storage unit. The generated electricity was supplied to an alkaline electrolysis unit for hydrogen production. In this unit, G and Ag-Cu/G used as cathode electrodes, while platinum was utilized as the anode electrode. Hydrogen production was analyzed for each electrode configuration.

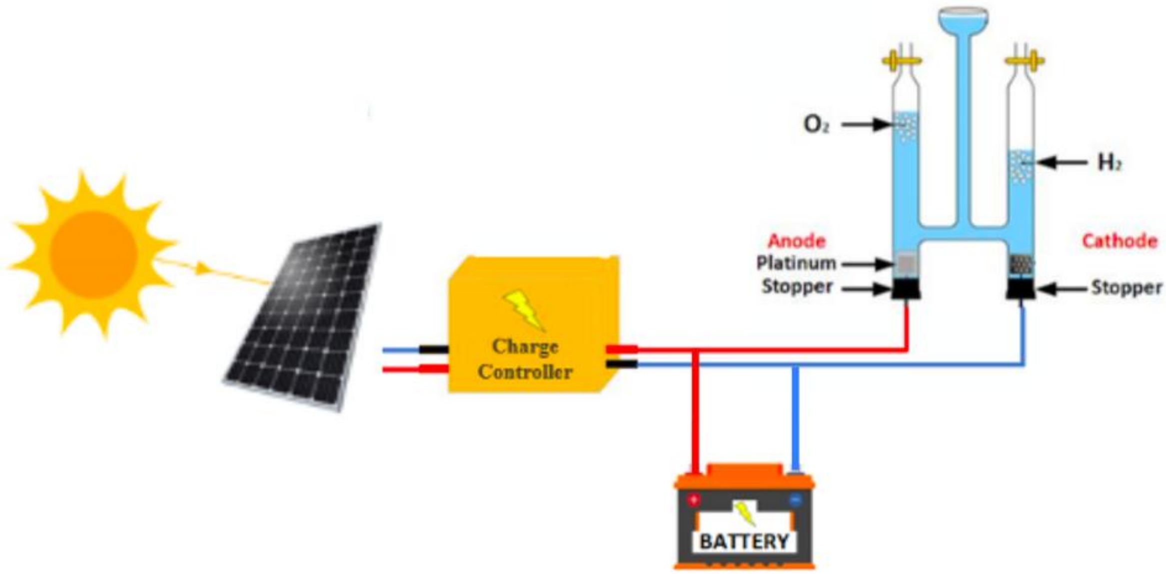

Figure 1. Alkaline electrolysis system powered by solar PV panel.

Climatic data for the Adana region in 2024, including the average number of sunny, cloudy, and rainy days for each month during the spring and summer seasons, were incorporated into the simulations. Data from March, April, and May were used for the spring season, while June, July, and August data were used for the summer season. This information is summarized in Table 2.

Table 2. Number of sunny, cloudy and rainy days in spring and summer

Spring		Summer	
March 2024	Precipitation: 5 days; Cloudy: 11 days; Sunny: 15 days	**June 2024**	Precipitation: 1 days; Cloudy: 5 days; Sunny: 24 days
April 2024	Precipitation: 4 days; Cloudy: 12 days; Sunny: 14 days	**July 2024**	Precipitation: 7 days; Cloudy: 3 days; Sunny: 21 days
May 2024	Precipitation: 14 days; Cloudy: 8 days; Sunny: 9 days	**August 2024**	Precipitation: 3 days; Cloudy: 3 days; Sunny: 25 days

In the simulations, average daily solar radiation levels and temperature variations for each month were considered based on this climatic data. The simulation was conducted based on the data provided in Table 3, which presents the hourly solar radiation and temperature values for sunny, cloudy, and rainy days in the Adana region for 2024. The table classifies each type of day based on the corresponding average temperature and solar irradiance values at different hours. This detailed analysis enables precise modeling of the solar panel's performance under diverse climatic conditions. By incorporating these specific hourly values, the simulation effectively replicated real-world conditions, enabling a comprehensive assessment of how different weather patterns influence the energy generation capacity of the 80W solar panel. This approach ensured that the results reflected the dynamic changes in temperature and radiation levels typical of Adana's seasonal variations, providing a comprehensive understanding of the system's efficiency under different environmental conditions.

Ag-Cu coating was formed by chronopotentiometry under 50 mA cm^{-2} current density [23] in 30% $CuSO_4.5H_2O$, 1.25% $C_4H_6O_6$ (tartaric acid), 1.25% $AgNO_3$, 1.25% H_3BO_3 bath, the counter electrode was Cu sheet %99.9 (1x1x0.2 cm). The operation time was calculated based on Faraday's laws for a film thickness of 10 µm. Electrolysis was conducted using a two-electrode configuration, and the volume of hydrogen gas accumulated at the cathode was measured in an inverted graduated cylinder over a 15-minute period.

3. Results and Discussion

The calculations were carried out considering the daytime durations and the duration of the day with high radiation, as depicted in Figure 2. The red bars represented the total daylight hours for each month from March to August 2024, while the orange bars showed the duration of the day when solar radiation was high enough for efficient energy production. In the simulation, only the hours with high solar radiation were considered for effective energy generation by the 80W solar panel. For instance, in March, although the total daylight duration was around 12 hours, the high radiation period was approximately 6 hours, which was used for power generation calculations. Similarly, for other months, the actual power generation duration was derived from the portion of the day with high radiation, aligning with the brown bars in the graph. This approach ensured that the calculations reflected realistic conditions for solar panel performance, acknowledging that not all daylight hours contribute equally to energy generation. The results thus provided a more accurate representation of the monthly energy production potential of the solar panel under varying radiation conditions throughout the day.

Table 3. Radiation and temperature values in spring and summer

Month	Sunny Days		Cloudy Days		Rainy Days	
	Radiation (W/m²)	Temp. (°C)	Radiation (W/m²)	Temp. (°C)	Radiation (W/m²)	Temp. (°C)
March 2024	840	20	450	18	200	18
April 2024	865	27	460	24	200	24
May 2024	980	32	500	29	200	25
June 2024	1000	36	500	34	200	31
July 2024	1000	40	520	37	200	36
August 2024	980	39	510	37	200	36

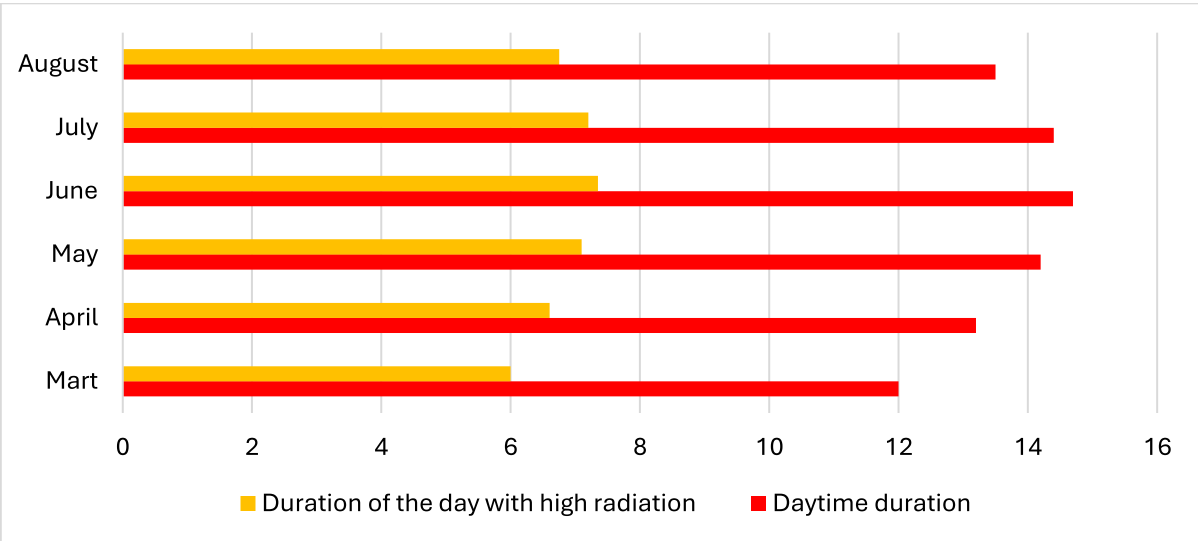

Figure 2. Daytime duration and effective duration of radiation (hours).

The comparison of monthly energy production revealed significant variations across different months, primarily influenced by the number of sunny, cloudy, and rainy days, as well as the duration of daylight hours with high solar radiation. March, with a total generation of 9567.12 Wh, experienced a relatively balanced distribution of sunny and cloudy days, but its energy production was hindered by rainy days. April saw an improvement with 11204.778 Wh due to an increase in sunny days and longer daylight hours, despite a few additional cloudy days. In contrast, May recorded the lowest total production, 9046.221 Wh, mainly due to a higher frequency of rainy days, which significantly reduced overall energy output, even though daylight hours continued to increase.

Table 4. The total power generation values of sunny, cloudy and rainy days according to the months.

Months	Number of Sunny Days	Power Generation (Wh)	Number of Cloudy Days	Power Generation (Wh)	Number of Rainy Days	Power Generation (Wh)	Total Power Generation (Wh)
March 2024	15	6598.80	11	2496.42	5	471.90	9567.12
April 2024	14	7618.05	12	3186.24	4	400.48	11204.77
May 2024	9	5268.07	8	2281.04	14	1497.09	9046.22
June 2024	24	14303.97	5	1484.7	1	105.10	15913.78
July 2024	21	12254.06	3	872.64	7	720.72	13847.42
August 2024	25	13691.37	3	818.10	3	289.72	14799.20

June marked the peak of energy production at 15913.781 Wh, driven by the highest number of sunny days and the longest daylight duration of 14.7 hours, making it the most productive month for solar energy. July, with 13847.424 Wh, and August, with 14799.2 Wh, also showed high levels of production, benefiting from a similar pattern of extended daylight hours and predominantly sunny days. However, the slight drop in July's total was due to an increase in rainy days compared to June. The results highlight that although the number of sunny days is a key factor, the extended daylight hours and lower cloud coverage during the summer months play a more significant role in enhancing the energy generation potential of solar panels in Adana (Table 4).

In Figure 3, the graph illustrates the power output of an 80W solar panel in Adana, measured in watts, across different weather conditions -sunny, cloudy, and rainy days- from March to August. On sunny days, the panel operated at nearly its maximum capacity, consistently producing around 80W of power. This highlights the optimal performance of the panel under clear-sky conditions. However, on cloudy days, the power output dropped significantly, averaging between 40W to 50W due to reduced solar irradiance. The impact was even more pronounced on rainy days, where the power generation plummets to around 15W-20W, reflecting the minimal sunlight reaching the panel. This data clearly demonstrated how the solar panel's efficiency was directly influenced by weather conditions, with the highest energy production occurring during the summer months of June, July, and August, which had more sunny days. In contrast, the spring months -March, April, and May- experienced lower energy output due to an increased number of cloudy and rainy days. This seasonal variation emphasized the importance of considering local weather patterns when planning for solar energy utilization in Adana.

The FESEM images of the Ag-Cu/G electrode, displayed in Figure 4a–b, highlight its rough surface morphology, which results from the electroplating of Ag and Cu particles. The electrode surface clearly indicates the successful deposition of these metal particles. Additionally, the EDX mapping in Figure 4c demonstrates a uniform distribution of Ag and Cu elements across the surface, confirming the homogeneous nature of the electroplated coating. The Ag and Cu ratio is 4.5 and 95.5%, respectively. The rough and evenly distributed surface is critical for enhancing hydrogen gas production [24-26]. A rough morphology increases the active surface area available for electrochemical reactions, thereby boosting catalytic performance [27-29].

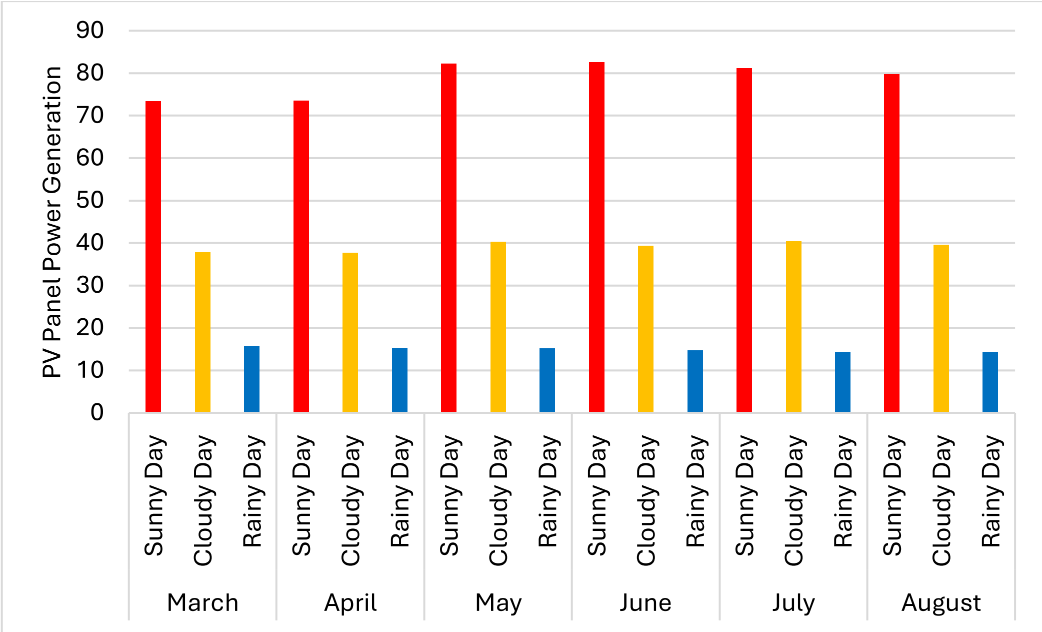

Figure 3. Monthly instantaneous power generation values of 80W solar PV panel according to weather conditions.

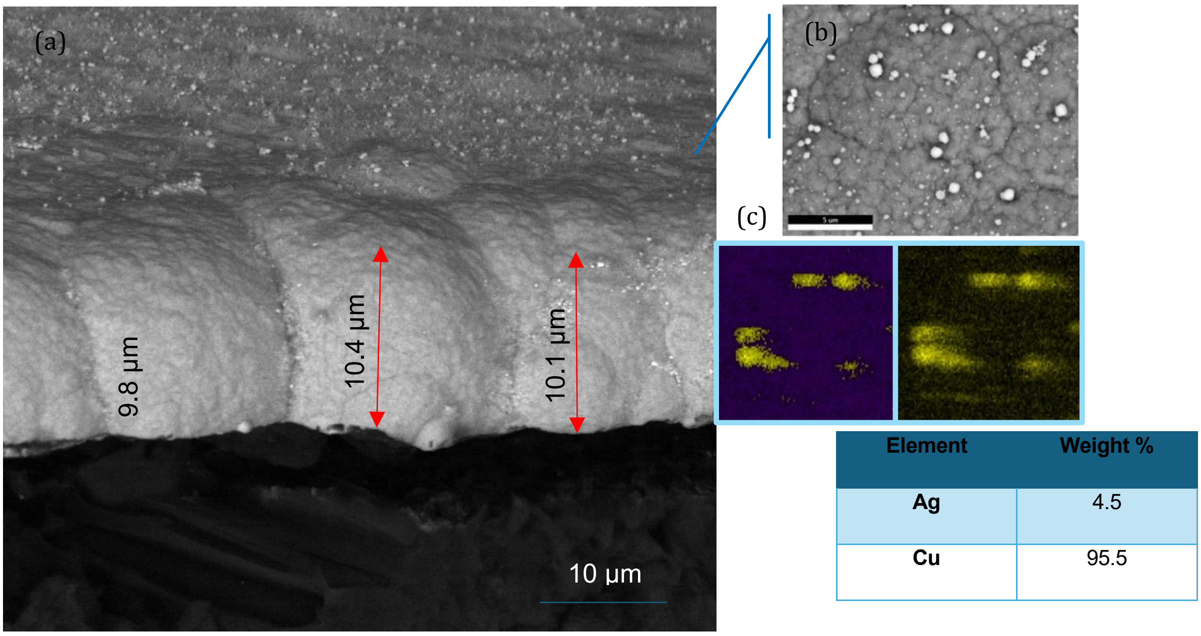

Figure 4. The cross section (a), top view (b) SEM micrograph of catalyst and EDX mapping analysis (c).

Table 5 presented the hydrogen volumes generated during 15 minutes of electrolysis in 1 M KOH at various applied voltages using different cathodes. The G cathode produced 15 mL of hydrogen at 3 V. For the Ag-Cu/G cathode, hydrogen volumes increased progressively with the applied voltage, starting at 13.7 mL cm^{-2} at 2.5 V and reaching 21.4 mL cm^{-2} at 3 V. This trend demonstrated the enhanced hydrogen production efficiency of the Ag-Cu/G cathode, particularly at higher voltages, compared to the unmodified graphite cathode. The synergistic interaction between Ag and Cu may have contributed to enhanced hydrogen evolution performance. Ag is well-known for its high electrical conductivity and electrocataytic activity; Cu can help with hydrogen adsorption and desorption procedures, thereby producing a more active catalytic surface. This combination likely improves electron transfer and optimizes the reaction kinetics, leading to the observed increase in hydrogen production.

Table 5. The produced hydrogen volumes.

Cathode@V		$V\ H_2$ / mL cm^{-2}
G@3.0		15.0
Ag-Cu/G	@2.5	13.7
	@2.6	15.1
	@2.7	17.3
	@2.8	19.2
	@2.9	20.1
	@3.0	21.4

4. Conclusions

The possibility for producing hydrogen in the Adana region using solar energy was examined in this study, along with the impact of various electrode materials. Alkaline electrolysis and simulations using an 80W solar panel showed that high temperatures have an adverse effect on panel performance and that solar radiation levels directly influence PV panel efficiency. The results showed that energy production was higher in the summer months due to longer daylight hours and a higher number of sunny days. Despite the high temperatures in summer, the increased total solar radiation contributed to higher energy output. In contrast, during the spring months, the high number of rainy and cloudy days limited the total sunlight exposure, resulting in lower energy production. It was observed that the Ag-Cu/G cathode electrode provided the highest hydrogen yield; however, production was lower during the spring months due to limited sunlight hours compared to the summer. These findings highlight the feasibility of hydrogen production using solar energy in regions with high solar potential like Adana, while emphasizing the need to consider seasonal variations and temperature management to enhance system efficiency. In order to enhance the performance of such systems and evaluate their wider applicability, future research should concentrate on a variety of enhancements and integration techniques. These findings are important for optimizing solar energy systems and evaluating the potential for hydrogen production in regions with similar climatic conditions.

Authors' Contributions

BDM: Conceptualization, Methodology, Resources, Writing - Original Draft, Writing - Review & Editing, Validation, Supervision. **HN:** Data Curation, Writing - Original Draft, Software, Validation. **MEM:** Data curation, Visualization, Investigation, Writing - Original Draft.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

There is no conflict of interest in this study.

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