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The Hydrogen Potential Assessment based on Wind and Solar Energy in Elazig Province, Türkiye

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Abstract: This study investigates the feasibility of hydrogen production potential using the available renewable energy source potentials in the province of Elazig, Türkiye. The study aims to create a potential assessment of each district in Elazig, based on wind and solar sources and Proton Exchange Membrane (PEM) electrolyzer technology. It aims not only to evaluate the green hydrogen potential but also to outline the feasibility of implementing this alternative energy source at a localized level. In this way, an alternative energy source can be assessed for production, storage, and the scarcity of energy in emergency conditions such as earthquakes or other cases. The comprehensive analysis integrates a multitude of parameters, including geographic variations and technological considerations, supported by detailed illustrations to present a holistic view of the hydrogen potential in Elazig. The study's outcomes suggest that districts with high energy potential and minimal geographical and topological constraints have a significant potential for hydrogen production.

Key words: Green Hydrogen, Wind Energy, Solar Energy, PEM Electrolyzer.

Türkiye'nin Elazığ İlinde Rüzgar ve Güneş Enerjisine Dayalı Hidrojen Potansiyelinin Değerlendirilmesi

Öz: Bu çalışma, Türkiye'nin Elâzığ ilinde mevcut yenilenebilir enerji kaynaklarının potansiyeline dayanarak hidrojen üretim potansiyelinin fizibilitesini araştırmaktadır. Çalışma, rüzgâr ve güneş kaynaklarına ve Proton Değişim Membranlı (PEM) elektrolizör teknolojisine dayalı olarak Elazığ'daki her bir ilçenin potansiyel değerlendirmesini oluşturmayı amaçlamaktadır. Sadece yeşil hidrojen potansiyelini değerlendirmeyi değil, aynı zamanda bu alternatif enerji kaynağının yerel düzeyde uygulanmasının fizibilitesini de ortaya koymayı amaçlamaktadır. Bu şekilde, alternatif bir enerji kaynağı üretim, depolama ve deprem gibi çeşitli acil durumlarda enerji kıtlığı için değerlendirilebilir. Kapsamlı analiz, Elazığ'daki hidrojen potansiyelinin bütüncül bir görünümünü sunmak için ayrıntılı görsellerle desteklenen coğrafi varyasyonlar ve teknolojik hususlar da dahil olmak üzere çok sayıda parametreyi içermektedir. Çalışmanın sonuçları, yüksek enerji potansiyeline ve minimum coğrafi ve topolojik kısıtlamalara sahip ilçelerin hidrojen üretimi için önemli bir potansiyele sahip olduğunu göstermektedir.

Anahtar kelimeler: Yeşil Hidrojen, Rüzgâr Enerjisi, Güneş Enerjisi, PEM Elektrolizör.

1. Introduction

Reliance on fossil fuels is insufficient to meet persistent long-term energy demands, particularly in light of the depletion of these resources. Consequently, several key factors are driving the transition to renewable energy sources. These include their abundant availability, declining system costs, and the extensive development of electricity infrastructure [1]. Their intermittent nature, notably solar and wind energy, poses challenges for sustainability and operational efficiency. Consequently, there is a growing need for alternative sources such as hydrogen to mitigate these inherent challenges and reduce reliance on fossil fuels [2,3]. Hydrogen offers advantages like high energy density, abundance, long-distance transportability, storability, and zero-carbon emission. Based on these features, it is anticipated that hydrogen will be abundantly utilized in different sectors in the future. It is estimated that by 2050, nearly 20% of global energy demand will be met by hydrogen. Aligned with Türkiye's 2053 net-zero emissions targets and considering on-site consumption and industrial demands, the Turkish government has set an ambitious goal to achieve an electrolyzer capacity of 5.0 GW by 2035. This initiative reflects the nation's commitment to advancing hydrogen production as a key component of its sustainable energy strategy [4,5].

Hydrogen can be generated through various methods. Each method offers distinct processes and efficiencies, catering to different resource availability and application requirements. The feasibility and potential of hydrogen

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production from renewable energy sources have been widely analyzed in several studies. Mostafaeipour et al. [6] explored the hydrogen generation potential in Iran by utilizing wind energy. Certain wind turbines were identified as capable of meeting both the required energy load and the hydrogen fuel demand. Nematollahi et al. [7] conducted a techno-economic evaluation of hydrogen production by assessing the solar energy potential in Iran. Al-Sharafi et al. [8] investigated the hydrogen production potential in Saudi Arabia, analyzing different regions based on renewable capacity. These regions were compared primarily through the hydrogen production costs. Similarly, Iqbal et al. [9] assessed the hydrogen production potential across eight different sites in Pakistan, using wind energy. The evaluation was conducted based on technical and economic parameters. Rezaei et al. [10] focused on the hydrogen production potential using renewable energy and seawater aiming to enhance hydrogen production by ensuring easy access to water resources. Ayodele et al. [11] evaluated wind and hydrogen energy potential at different locations across South Africa. Katsigiannis et al. [12] examined the feasibility of hydrogen production using wind turbines, gas turbines, and solar systems. Bekele et al. [13] conducted a study to explore the general aspects and feasibility of wind energy utilization for hydrogen production. Several studies have investigated the hydrogen production potential in Türkiye from different energy sources, including solar [14], wind [15], hydroelectric [16], and other renewable resources. Arat et al. [17] focused on hydrogen-related studies conducted in Türkiye, analyzing academic and technical projects to provide guidance for future research. Dincer et al. [18] evaluated Türkiye's hydrogen potential from renewable sources in various selected locations. These studies aimed to assess the green hydrogen production potential of each resource being evaluated based on data provided by official institutions. Although numerous studies have been conducted on renewable energy and hydrogen at both national and international levels, research evaluating the hydrogen potential as an alternative energy source, particularly for emergency conditions, remains limited.

This paper presents an assessment of the hydrogen potential in the province of Elazig, Türkiye. The idea is to assess different parts of Elazig for hydrogen potential by renewable energy sources. The novelty of this paper lies in its integrated assessment of hydrogen potential in Elazig, Türkiye, against the backdrop of recent seismic events in 2023 that caused significant disruptions in fuel and energy supplies. The study strategically identifies safe zones of Elazig with high hydrogen production potential. This innovative approach not only aims to address energy scarcity during emergencies but also proposes a solution for energy transportation and storage by utilizing hydrogen from surplus electricity to aid areas in need. The paper offers meaningful insights into the potential of hydrogen production and contributes to the national hydrogen strategies and objectives of Türkiye.

2. Material and Method

The generation of hydrogen through the renewable energy sources, combined with the electrolysis process, represents one of the cleanest methods of hydrogen production. Figure 1 offers a visual illustration of the hydrogen generation process.

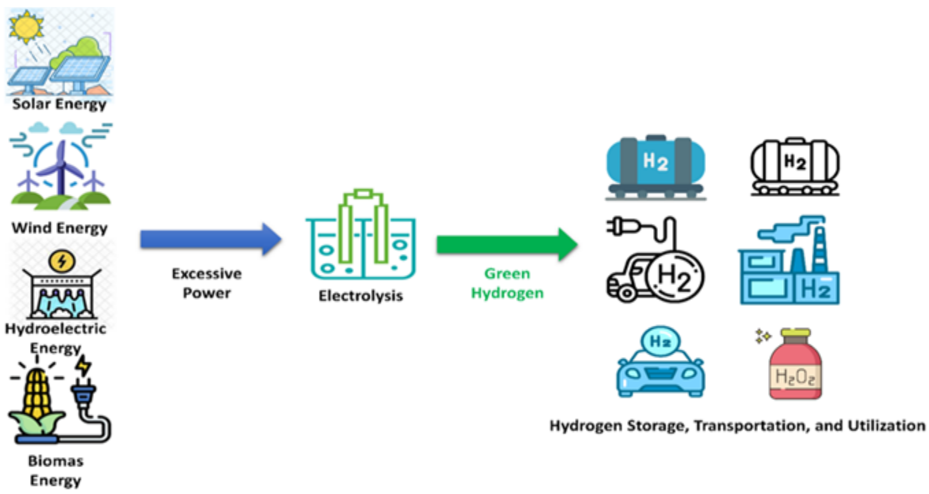

Figure 1. Renewable energies based green hydrogen production.

As illustrated in Figure 1, the diagram emphasizes the flexibility of electrolysis in capturing energy from renewable sources such as solar, wind, and other clean energy technologies for hydrogen production. Excess renewable energy is channeled into the electrolysis process, which is a highly efficient method of producing hydrogen [19]. This chemical process is referred to as green hydrogen production. The hydrogen generated through this process has various applications, including transportation, industrial, residential, commercial, chemical, and agricultural sectors. For the production of 1 kg of hydrogen, approximately 9 liters of water are required for the electrolysis process. Different electrolyzer configurations exist, such as Alkaline (AEL), Polymer Electrolyte Membrane (PEM), and Solid Oxide Electrolyzers (SOE) [20]. PEM electrolyzers, in particular, are noted for their high efficiency rapid response times, operating at lower temperatures, and higher current densities, positioning them as leading technologies for green hydrogen production [21].

2.1. Potential assessment

The research conducted in this study centers the geographical area of Elazig, Türkiye. Situated within coordinates of 38° 38´ N latitude and 39° 20´ E longitude, this region encompasses a notable altitude of approximately 1067 m (3501 ft). The unique geographical layout of Elazig is characterized by its geographical resemblance to an inland peninsula, encircled by Lake Hazar and reservoirs formed by the Keban and Karakaya Dams. Figure 2 provides a visual representation of the map view detailing the geographical layout of Elazig, highlighting its distinctive topographical features and the spatial relationships of its districts within this province.

Figure 2. The general view of Elazig province.

The province offers a diverse range of renewable energy opportunities across its area. This study primarily focuses on evaluating the hydrogen production potential from wind and solar energy. The assessment involves analyzing various locations within the province to determine their viability for hydrogen generation. Figure 3 provides a detailed map that illustrates the wind energy potential across the different regions of the province.

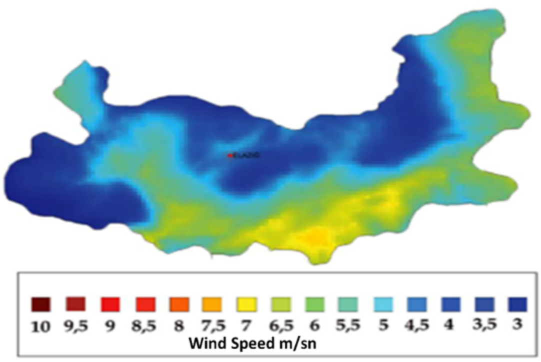

Figure 3. The wind potential map of Elazig province

Figure 3 highlights specific areas within Elazig that display varying levels of wind energy potential. The data for wind energy potential in this study were sourced from the State Meteorology Service, with wind speed measurements taken at a height of 50 meters above ground level These assessments are essential for identifying optimal sites for wind energy projects. By selecting the locations with elevated wind potential, wind energy systems can generate electricity more efficiently, thereby enhancing the potential for hydrogen production [22]. In Elazig, the southern and southeastern regions exhibit higher wind energy potential compared to other parts of the province. To estimate the total wind energy potential, the overall area of the province was calculated using official data. The average wind speed at 50 meters in Elazig is recorded at 4.4 m/s.

Solar energy is abundant, widely available, and most importantly, freely accessible. These characteristics make it particularly beneficial for use in rural areas and off-grid locations, where access to the conventional electric grid can be limited or nonexistent [23]. The solar energy potential of the province is depicted in Figure 4, which illustrates a relatively uniform distribution of solar potential across the region. Solar radiation data were obtained from official Ministry resources and solar energy databases.

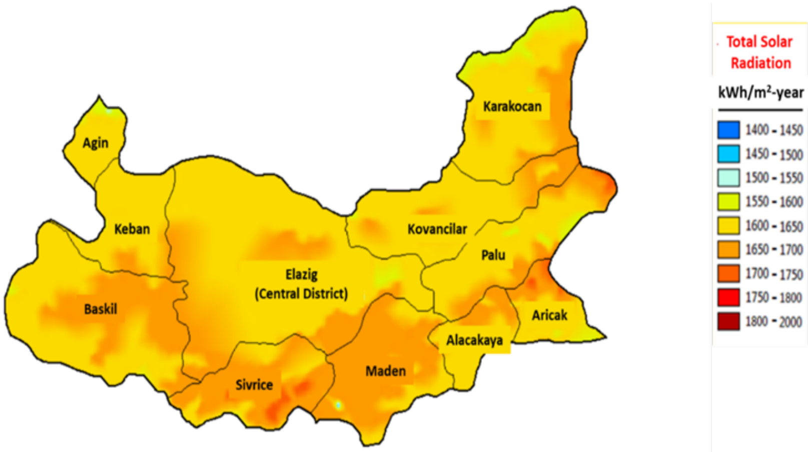

Figure 4. The solar potential of Elazig province.

As shown in Figure 4, there is a high potential for solar energy, particularly in the southern areas of the province. The presented data shows that the average solar potential in these regions varies significantly, ranging between 1550 and 1750 kWh/m² per year.

2.2. Component specifications

When evaluating the potential for hydrogen, it is necessary to consider the characteristics of the components to be used for both electricity and hydrogen production. These characteristics are crucial in comprehending the performance of the components, which contributes to the calculations related to hydrogen potential assessment within the study. Table 1 provides a comprehensive summary of the specifications associated with the selected electrolyzer technology.

Table 1. The specifications PEM electrolyzer [24].

Model Name	H-TEC PEM Electrolyzer ME450
Net Production Rate (Nm3/h)	42 – 210 Nm³/h
Production Capacity Range (%)	20 – 100 %
Power Consumption at Stack (kWh/Nm3)	4.7 kWh/Nm³ | 53 kWh/kg
H_2 Purity	5.0
Ambient Temperature (C)	-20°C to +40°C
System efficiency	75 %

Proton Exchange Membrane (PEM) electrolyzers operate on the same fundamental principles as other water electrolysis technologies, where water is electrochemically split into hydrogen and oxygen using electrical energy. The working principle is shown in the Figure 5.

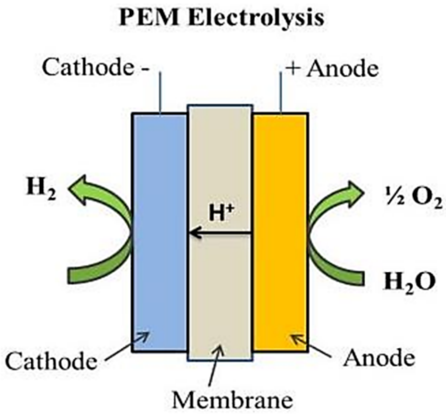

Figure 5. The working principle of a PEM electrolyzer.

For the electrolyzer, a defined quantity electricity is required to be applied to both electrodes. These electrodes are isolated from each other by an electrolyte characterized by high ionic conductivity. This application facilitates the decomposition of water into its elements, hydrogen, and oxygen in the electrolysis process. This process is described by the following equations [25].

$$Anode: H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \quad (1)$$

$$Cathode: 2H^+ + 2e^- \rightarrow H_2 \quad (2)$$

$$Overall\ reaction: H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (3)$$

The expressions in Equations (1-3) are utilized to carry out the necessary modeling and analysis for the conversion of hydrogen into electricity.

PV panels generate electricity by converting sunlight into electrical energy through the solar cells. The method produces electricity without emitting pollutants, contributing to cleaner and greener energy generation [25]. In this study, mono-facial monocrystalline PV panels were employed for harnessing solar energy. The specific characteristics of the chosen PV panels are systematically presented in Table 2.

Table 2. The PV panel specifications [26].

Model Name	Canadian solar HiKu6 Mono PERC 400MS
Cell Type	Mono-crystalline
Nominal Max. Power (Pmax)	400 W
Max. System Voltage	1500V (IEC/UL)
Module Efficiency	20.5%
Operating Temperature	-40°C ~ +85°C

The electrical output of PV panels P_{PV} is given in Equation (4).

$$P_{PV} = Y_{PV} \times f_{PV} \left(\frac{G_T}{G_{T,SC}}\right) \times [1 + a_f(T_C - T_{C,SC})] \quad (4)$$

Where:
Y_{PV}: Rated power value of PV panels under standard conditions (SC) (kW)
f_{PV}: PV panels derating factor (%)
G_T: Solar irradiation value on PV panels (kWh/m^2)
$G_{T,SC}$: Standart irradiation value (1 kWh/m^2)
a_f: PV panel temperature coefficient (% °C)
T_C: PV cell temperature (°C)
$T_{C,SC}$: PV cell standard temperature (25 °C)

If the local wind velocity is denoted as V, with air density represented by ρ, and A as the swept area of the rotating blades of the wind turbine, the potential wind energy can be mathematically expressed as follows:

$$W = \frac{1}{2} \times \rho \times A \times V^3 \quad (5)$$

The potential for a given wind speed is expressed as described above. Wind speeds vary with altitude levels. The Hellmann Equation serves as a common method for estimating wind speeds at different altitudes of a wind turbine. [27]. The equation can be expressed as in Equation (6).

$$\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^{\propto} \quad (6)$$

Where:
H_0 is the reference height,
V_0 is the wind speed at the reference height,
H is the height at which the wind speed is to be calculated,
V is the wind speed at height
$\propto$ is the friction coefficient, a value that varies according to the topology of the area exposed to the wind. The power captured by a wind turbine can be quantitatively described using fundamental aerodynamic principlesThis relationship can generally be expressed in the form of the power equation of a wind turbine in Equation (7).

$$P = \frac{1}{2} \times C_P \times p \times A \times {V_W}^3 \quad (7)$$

Where:
P is the power extracted from the wind (watts),
ρ is the air density (kg/m³),
A is the swept area of the turbine blades (m²),
V_W is the wind speed at the turbine level(m/s),
C_P (λ, β) is the power coefficient, which depends on the tip speed ratio (λ) and the blade pitch angle (β). This parameter represents the energy conversion efficiency of a turbine. C_P is critical to wind turbine design and efficiency, influenced by blade aerodynamics, rotor integrity, and control strategies. The theoretical maximum, known as the Betz Limit, is 59.3%. Under normal conditions, this value can be maintained between 45% and 55% with effective control strategies, ensuring efficient operation. The proposed study utilizes onshore-type wind turbines featuring horizontal axis turbines as the chosen wind energy conversion system. The usage of these types aligns with specific considerations and requirements, and the turbine specifications are tabulated as Table 3.

Table 3. Wind turbine specifications [28].

Model Name	EWT DW 54
Rotor diameter (meters)	50
Rated Power (kW)	900
Cut-in wind speed (m/s)	3
Cut-out wind speed (m/s)	25

The power curves, which details the relationship between power output and wind speed, play a pivotal role in the analysis of the selected turbine's generation potential under varying atmospheric conditions. Characteristic curves for the selected model are shown in Figure 6.

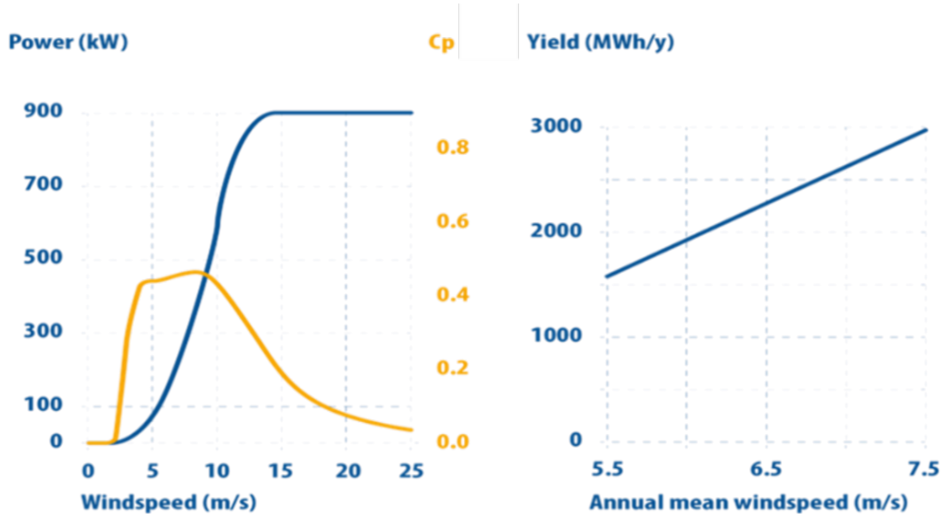

Figure 6. The solar potential of Elazig province.

As depicted in Figure 6, wind speeds exceeding the minimum threshold initiate electricity generation. The variation of the power coefficient (C_P) between 0.45 and 0.55 (yellow curve) highlights the critical role of adaptive control systems. These controls adjust operational parameters in real-time to ensure that C_P remains within this optimal range, thereby maximizing energy output and contribute to effective electricity generation. The power (Yield) curve relative to wind speed values is derived from measurements taken at the tower hub level. With the annual average wind speed, it is estimated that approximately 1000 MWh/year of electricity can be generated in the selected province.

The geographical restrictions are the excluded areas in different parts of the province. These limitations are crucial in identifying the specific areas where energy conversion systems will be implemented. The territory gets more rugged in the south and southeast districts (Sivrice, Maden Alacakaya, Aricak, Palu) [17]. Approximately 80% of the province's territory is utilized, considering topological constraints and other relevant factors. To account for these variations, the study introduces the topological coefficient parameter (α). This coefficient provides a systematic approach to evaluating the suitability of the terrain for energy conversion projects. The topological coefficient is determined through a detailed analysis of geographic maps and comprehensive evaluations of all designated areas [20]. The specific topological coefficients for each district are provided in Table 4, offering a quantitative representation of the topological considerations inherent in the study's analysis.

Table 4. The topological coefficients for Elazig province.

	Area (km2)	The topological coefficients
Elazig (Central District)	2243	0.47
Agin	242	0.05
Alacakaya	318	0.06
Arıcak	354	0.07
Baskil	1318	0.28
Karakocan	1049	0.22
Keban	641	0.121
Kovancılar	960	0.2
Maden	819	0.17
Palu	730	0.156
Sivrice	710	0.15
Total	8343	

The yearly electricity consumption of the whole province was obtained from the energy distribution company and other institutes. Although the electricity consumption is calculated as Wh, the hydrogen production based on renewable energy sources expressed as megatons (Mt). To ensure equivalence between different units, these values are converted to an equal unit of electricity, produced as Mt of hydrogen. According to these assumptions, the yearly electricity consumption of the province is about 0.02 Mt/per year [18].

3. Results and discussions

Solar energy, changes in various districts according to different solar radiation and insulation values. For the city center and the districts, monofacial PV panels are assessed with an efficiency of 20.5% The other option, bifacial PV arrays, are commonly utilized for floating (on-water) applications. For wind turbines, hub height for a wind turbine can be adjusted based on population distribution and geographical conditions. Horizontal-bladed high tower turbines are utilized in scarcely populated districts. This type turbines are not applicable in densely populated and agricultural areas [1]. Theoretically, 1 kg of hydrogen production requires 117650 kJ of energy for the production process. The efficiency of the selected electrolyzer is regarded as 75%. Therefore, the required energy for hydrogen production (W_{actual}) is approximately calculated as:

$$W_{actual} = \frac{117{,}650}{0.75} = 158866\ kJ \tag{8}$$

As described in Equation (8), the selection of the electrolyzer type determines the production characteristics. In this analysis, it is assumed that 60% of the total potential power (90000 kj) will be generated by wind turbines, while the remaining 40% (68866 kj) will be supplied by the reference solar panels. The evaluation of hydrogen potential can be conducted in the city center and other districts by using the energy equivalent of 1 kg hydrogen. Based on the average wind speed and solar potential across the province, the estimated hydrogen production potential is approximately 11.9 Mt for 1 kg H_2. Hydrogen potential based on this value can be mapped by assessing each district's hydrogen potential. This involves a comprehensive evaluation of factors such as renewable energy availability, topological constraints, and other relevant parameters for each district. By conducting this, a spatial representation can be generated to visually depict the varying degrees of hydrogen potential across the entire province [6]. In light of this information, Figure 7 provides a colorized map of the province showing total hydrogen potential based on the available renewable power.

Figure 7. Hydrogen production potential of Elazig from excess power.

In Figure 7, each color represents potential variation, ranging from light to dark tones. The produced energy is firstly provided for load demand from different parts of the province and the excess power is utilized for electrolyzer systems. Districts with more available land and higher altitudes tend to have greater hydrogen production potential. Dark-colored areas, such as Elazig (central district), Baskil, and Kovancilar, demonstrate higher potential compared to other districts. Although Karakocan exhibits substantial potential, the presence of topographical challenges, as outlined in Table 4, reduces the hydrogen potential for this district. Similarly, other districts face diminished potential due to a combination of topographical limitations and various environmental factors. Notably, districts located near water reservoirs, particularly in the northern and western parts of the province, exhibit significantly greater potential for hydrogen production compared to other regions. Figure 8 provides a graphical representation of the relative contributions of each district to the overall hydrogen potential.

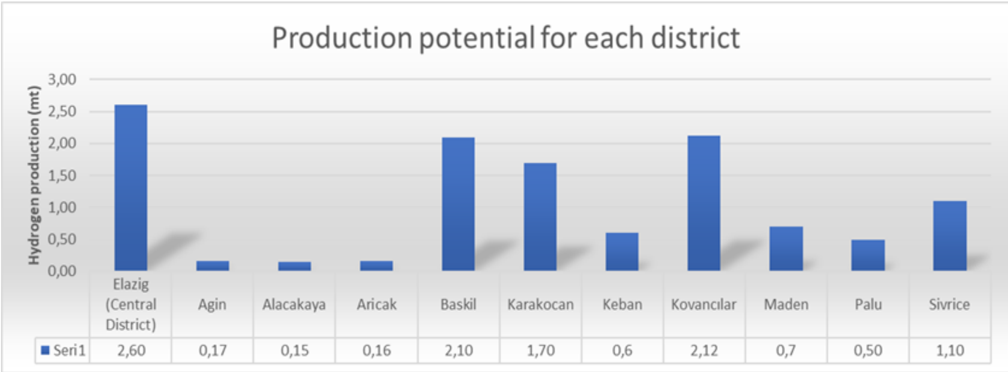

Figure 8. Hydrogen potential graph for each district.

Figure 8 highlights the proportional hydrogen production across different districts, offering insights into regional variations in production efficiency and capacity. Furthermore, it enables researchers, policymakers, and stakeholders to comprehend and analyze the distribution and magnitude of hydrogen potential for the area. The number of components required per kilogram of hydrogen is another critical parameter for evaluating production potential. Table 5 presents values derived from the selected wind turbine and solar panel data.

Table 5. The number of components required per kilogram of hydrogen.

Components	Required power for per component (kJ)	Numbers* Selected Model
Wind Turbine	90000	1* EWT DW 54
Solar Panel	68866	50*PERC 400MS

To determine the number of energy conversion components required per unit of hydrogen production, the study considered the average wind speed and solar radiation values of Elazığ, along with the efficiency values of the selected components. The overall efficiency of the solar panel was assumed to be 20%, as determined by its standard characteristic value. The wind turbine's general efficiency, depicted in Figure 6, was estimated to be approximately 40% based on average wind speed values. Calculations were performed based on the power contributions from wind turbines and solar panels, expressed relative to the energy demand for producing one kilogram of hydrogen in kilojoules. For the selected electrolyzer technology, it was determined that the required energy could be supplied by combining 1 wind turbine and 50 solar panels.

4. Conclusions

Hydrogen can become an important means of renewable energy storage and transportation over long distances and a long period. The main idea related to hydrogen is to create a promising clean, and more durable energy source and an essential component for further development. Due to its geopolitical location, Türkiye is rich in retaining various types of renewable energy resources. By using these sources, the utilization of fossil fuels could decrease and provide clean sustainable energy for different parts of Türkiye. This study provides an in-depth analysis of the potential for hydrogen production in various districts of Elazig, Türkiye. The available renewable potentials for each district are discussed comprehensively, shedding light on the unique factors that influence hydrogen production in the region. The study presents innovative ideas to deal with the fossil fuel usage, and energy scarcity problems for the province, as well as the region. It has been observed that districts with high energy potential and low restrictions have a high potential for hydrogen production. The results prove that renewable energy potential for the province is convincing for hydrogen productibility. In this way, greenhouse gas emissions will be reduced and a carbon-free province and eco-friendly hydrogen production will be possible. Furthermore, the results fulfill a concise guide to enable different sectors to use renewable energy potentials for hydrogen production. Future research will involve conducting various simulations and real-time experimental studies using different configurations of renewable energy sources for the province. These studies will be based on real-time meteorological data and on-site assessments to enhance the accuracy and applicability of the findings.

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