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Research Article

Modeling and optimization of hybrid hydro-solar-wind systems for green hydrogen production in Togo

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Abstract. This study examines the feasibility and optimization of hybrid hydro-solar-wind-hydrogen energy systems in Togo, focusing on seasonal variations and energy management. Data on solar radiation, wind speed, and hydropower were obtained from meteorological stations, satellite databases, and the Nangbéto station. The results of this study show that the energy management system at the Nangbéto dam could rely on hydrogen storage and a 2.75 MW fuel cell to balance seasonal fluctuations, while a ±3 MW battery would stabilize power output. During periods of high hydropower production, surplus energy could be converted into hydrogen to ensure a continuous supply during low-flow months. The flow fluctuates seasonally, ranging from 1.5–20 m^3/s in dry months to over 120 m^3/s in the wet season, affecting hydrogen production (5–25 kg/day). Electrolysis efficiency remains stable (65–85%) due to optimized management. The hydro-solar-wind hybrid system converts up to 20% of hydropower into hydrogen, with peak production in August (~1,700 kg/month). Selected sites over Togo, particularly Blitta and Alédjo, show potential for hydrogen infrastructure, with Blitta yielding the most hydrogen (532.15 kg annually) and Lomé the least (482.72 kg) due to differences in solar irradiance. The study highlights the role of energy storage, hybrid integration, and policy support to enhance Togo's hydrogen production and long-term energy stability.

Keywords: Hybrid energy systems, Energy storage, Renewable energy, sustainability, Togo.

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1. Introduction

The transition to sustainable energy systems is a global priority, particularly in regions where energy insecurity remains a major barrier to economic and social development (Brodny *et al.* 2020, Pinchao *et al.* 2024). In West Africa, energy challenges are characterized by a high dependence on imported electricity and fossil fuels, low electrification rates in rural areas, and grid instability (Kokou *et al.*2022, Lamboni *et al.* 2024c). Despite the region's abundant renewable energy resources such as solar, wind, and hydropower the development of a reliable and efficient energy system remains insufficient. However, West Africa is home to some of the fastest-growing populations in the world, which places increasing pressure on existing energy infrastructure. According to the World Bank (2021), nearly 50% of the population in West Africa lacks access to electricity, with rural areas being the most affected.

Togo is a developing and low-income country characterized by deprived access to electricity as most Sub-Saharan African and West Africa countries. The existing access is such that it is nonuniform across the country. The rates of electrification in example, per region in 2019 are as follows: 96.70%, 65.52%, 23.84%, 31.61%, 33.91%, and 20.09%, respectively, for Lome, Maritime region, Plateaux region, Central region, Kara region, and Savana Region (ARSE, 2022). The urban areas are more electrified than the rural areas, with the capital city Lome being the most electrified through the years. Even within the towns, the access is not consistent. Up to 2020, the electricity access is still around 50% at the national level, leaving about 4 million inhabitants with no access to electricity (Kokou *et al.* 2022). Moreover, the country depends heavily on electricity imports from Ghana, Nigeria, and Côte d'Ivoire, making it vulnerable to external energy supply fluctuations and price volatility. Togo has large river network, where hydroelectric potential is estimated at 224 MW, which would correspond to an annual potential production estimated at 850 GWh (Sustainable Energy for All, 2012). Togo has significant solar potential varies from 4.4 kWh/m² to 5.5 kWh/m² with an average power density of 700 W/m². Wind energy potential also exists, particularly in coastal areas and certain high-altitude regions (Kokou *et al.* 2022, Lamboni *et al.*, 2024c). However, a lack of hybrid energy systems which combine different renewable sources limits the country's ability to efficiently harness and integrate these resources into the national grid. To address these challenges,

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the integration of advanced energy storage solutions, such as fuel cell and electrolyzer systems, presents a promising strategy. Electrolyzers can convert surplus electricity from renewable sources into hydrogen via electrolysis, enabling energy storage for later use (Hoang *et al.,* 2023b; Le *et al.,* 2025 Hussam *et al.,* 2024; Tarhan and Çil, 2021)., This hydrogen can then be utilized by fuel cells to generate electricity during periods of low renewable energy production or when demand is high (Noussan *et al.* 2021,). For instance, while solar energy is abundant during the day, wind energy can complement it at night or during periods of low solar intensity. Hydrogen, in turn, serves as an energy storage solution, allowing excess electricity generated from renewables to be stored and converted back into power when needed(Cao *et al.*, 2020; El-Shafie, 2023). This approach can significantly reduce energy losses, enhance grid stability, and minimize dependence on fossil fuels.

Several studies have demonstrated the benefits of hybrid systems in Africa. A study by Ouedraogo *et al.* (2022) in Burkina Faso highlighted how hybrid solar-wind systems significantly reduced electricity costs and increased energy access in rural areas. Similarly, research in Africa by Snousy *et al.,* (2025) demonstrated that bio-based hydrogen production through dark fermentation utilizing organic waste and biomass-could enhance energy reliability and reduce carbon emissions more effectively than traditional diesel generators, while avoiding resource constraints and high infrastructure costs. Given these successful implementations in neighboring countries, Togo stands to benefit from a similar integrated renewable energy approach. Rahmouni *et al.* (2017) conducted an evaluation of the potential for hydrogen production from both wind and solar photovoltaic panels. The outcomes revealed a range of hydrogen potential, with wind energy contributing between 18447.6 and 15705.3 tons per square kilometer per year, while solar energy accounted for a potential production of 6327.19 to 4437.14 tons per square kilometer per year.

Hydrogen production plays a crucial role in energy storage and decarbonization (Mukelabai *et al.,* 2022; Abdoulkader *et al.,* 2025). Excess electricity from renewable sources can be utilized for electrolysis, a process that splits water into hydrogen and oxygen. The hydrogen can then be stored and later converted back into electricity when solar and wind power generation is insufficient. This approach enhances energy autonomy and sustainability, making it particularly relevant for off-grid and remote areas in Togo. Additionally, hydrogen has diverse applications beyond electricity generation, including transportation and industrial processes, aligning with global efforts to develop a green hydrogen economy.

This study explores the feasibility and potential of hybrid solar-wind-hydrogen energy systems in Togo. By assessing the complementarity of these renewable energy sources, it aims to provide practical insights for optimizing their deployment. The research also focuses on modeling and evaluating the performance of an integrated fuel cell and electrolyzer system, with emphasis on key factors such as system efficiency and practicality. The findings will contribute to national and regional energy strategies, supporting West African countries in their transition towards a more resilient and self-sufficient energy future. Moreover, this study aligns with global sustainability goals and Togo's commitment to expanding renewable energy adoption under initiatives such as the CIZO solar program and the national electrification strategy (Présidence Togolaise, 2018). Addressing these challenges requires a comprehensive analysis of energy resource availability, system efficiency, and economic feasibility. Therefore, this research provides a scientific foundation for decision-makers, investors, and policymakers to promote large-scale renewable energy integration, reduce energy insecurity, and foster sustainable economic growth in Togo and beyond.

The rest of this paper is organized as follows: Section 2 describes the study area, data, materials, and methods used. Sections 3 and 4 present the results and discussion, while Section 5 concludes the paper.

2. Study area, Methods, data, and Materials

In this section, Study area, Methods, and Data Collection, Site Selection, Optimization and Simulation Tools are described.

2.1. Study area

The Republic of Togo, located in West Africa along the Gulf of Guinea, extends from latitudes 6˚N to 11˚N (Figure 1). It shares its borders with Ghana to the west, Benin to the east, and Burkina Faso to the north. The country's southern coastline stretches for 56 kilometers along the Gulf of Guinea. Encompassing a total area of 54,600 km², Togo exhibits a diverse topography, characterized by undulating hills in the northern regions, a central plateau in the south, and a low-lying coastal plain interspersed with extensive lagoons and marshlands. Togo faces significant socio-economic challenges, with approximately 69% of rural households currently living below the poverty line. The nation's climate transitions from tropical in the south to savanna in the north. The southern region is marked by high humidity levels and an average annual temperature of 27˚C, while the northern part experiences more pronounced temperature variations, fluctuating between 17˚C and 41˚C. Rainfall patterns in the southern regions follow a bimodal distribution, with the first rainy season extending from mid-March to late July and the second occurring from early September early to mid-November. Conversely, the northern regions experience a single rainy season, typically from May to October (Lamboni *et al,* 2024a). During the dry season, spanning from November to March, Togo is influenced by the Harmattan, a dry and dusty trade wind originating from the northeast, which

Fig. 1. Study area

brings cooler temperatures and arid conditions. Additionally, the northern regions are periodically affected by droughts (Lamboni, 2024b). Togo also benefits from substantial solar radiation throughout the year. Regarding wind energy potential, Togo experiences moderate wind speeds. Higher wind speeds are typically observed in elevated areas, such as coast, the central and northern plateaus (Kokou *et al.* 2022). A key component of Togo's energy infrastructure is the Nangbéto Hydropower Dam, located on the Mono River. Built in 1987, the dam is a binational hydroelectric project shared between Togo and Benin (Lamboni *et al.* 2024a). It has an installed capacity of approximately 65 MW, providing a significant portion of the country's electricity supply (Lamboni et al. 2024c). The reservoir created by the dam plays a crucial role in regulating water flow, preventing floods, and supporting irrigation. Despite its importance, the hydropower production at Nangbéto is subject to seasonal variability, with peak electricity generation occurring during the rainy season when water levels are high. During the dry season, reduced water inflows limit energy production, leading to an increased reliance on thermal power plants and imported electricity (Lamboni *et al.* 2024c). Given the intermittent nature of hydropower generation, there is a growing interest in integrating solar green hydrogen and wind energy into the national grid to enhance energy security and sustainability. The combination of hydropower, solar, wind and green hydrogen resources could significantly contribute to Togo's transition toward a more resilient and diversified energy mix.

2.2. Method

The integration of hybrid renewable energies in Togo relies on a rigorous methodological approach, combining data collection, modeling, and optimization to ensure a sustainable and efficient energy production. The Figure 2 illustrates this methodology by detailing the different steps of the process, from data acquisition to the evaluation of the hybrid system's performance. The methodology consists of the following key steps:

2.2.1. Assessment of Renewable Energy Potential

2.2.1.1. Methodology for Estimating Solar Power Generation Using GHI Data

The estimation of solar power generation relies on solar radiation data, specifically Global Horizontal Irradiance (GHI). Two widely used models for this purpose are the PVGIS (Photovoltaic Geographical Information System) and SAM (System Advisor Model). These models provide accurate predictions of photovoltaic (PV) energy output based on solar radiation, system efficiency, and local meteorological conditions.

2.2.1.1.1. Solar Power Generation Model

The power output P_{PV} of a photovoltaic system can be estimated using the following equation:

$$P\_{PV} = A * \eta * GHI \quad (1)$$

where: A is the total area of the photovoltaic panels (m²), η is the overall efficiency of the PV system (considering panel efficiency, inverter efficiency, and other losses), GHI is the Global Horizontal Irradiance (W/m²), which represents the total solar radiation received on a horizontal surface. This approach has been validated by studies such as Huld et al. (2012), who developed the PVGIS model for solar energy assessment in Europe and Africa. Additionally, Boretti, et al. (2020) highlighted the effectiveness of SAM in predicting PV performance in different climatic conditions.

2.2.1.1.2. Conversion of GHI to Tilted Irradiance

For PV panels installed at an optimized tilt angle, the Plane of Array (POA) irradiance (G_{POA}) is calculated as:

$$G\_{POA} = GHI * R\_b + DHI * (1 + \cos\beta)/2 + G\_{ground} * (\rho * (1 - \cos\beta)/2) \quad (2)$$

where: R_b is the ratio of beam radiation on the tilted plane to that on the horizontal plane; DHI is the diffuse horizontal irradiance, G_{ground} is the ground-reflected radiation, ρ is the ground reflectance (albedo), β is the panel tilt angle. Boretti *et al.* (2020) and Duffie & Beckman (2013) provide extensive methodologies for converting GHI to POA irradiance for inclined PV panels.

2.2.1.1.3. Estimation of Annual Energy Yield

The total annual energy yield (E_{PV}) of the PV system can be obtained by integrating the power output over time:

$$E\_{PV} = \Sigma (P\_{PV} * \Delta t) \quad (3)$$

where Δt is the time step (hourly or daily).

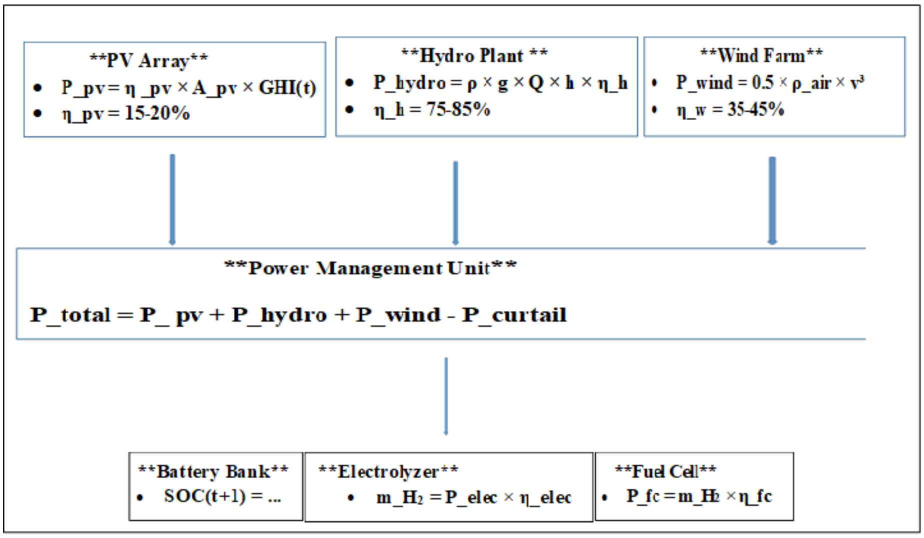

Fig.2. The research method process

Table 1
Parameters and Values for this study in Togo:

Parameter	Symbol	Value Range	Notes/Source
Panel Area	A	1-100 m²	Scalable based on system size
System Efficiency	η	15-20%	Includes all losses
GHI	GHI	180-250 W/m²	PVGIS data for Togo
Optimal Tilt Angle	β	10-15°	Latitude-adjusted
Ground Albedo	ρ	0.2-0.25	Typical for Togolese terrain
Sun Hours	Δt	4.5-5.5 h/day	Location-dependent
Performance Ratio	-	0.75-0.85	System quality factor

For a study in Togo (see Table 1), the parameters in Eqs. 1–3 include a panel surface area (A) of 1 to 100 m² (Eq. 1), a system efficiency (η) of 15–20% (Eq. 1), an average Global Horizontal Irradiance (GHI) of 180–250 W/m² (Eqs. 1–2), an optimal tilt angle (β) of 10–15° (Eq. 2), a ground albedo (ρ) of 0.2–0.25 (Eq. 2), and sunshine hours of 4.5–5.5 hours per day (Eq. 3). The methodology accounts for Togo's tropical climate conditions and aligns with established solar energy assessment practices for West Africa. This methodology aligns with previous studies, such as Sengupta et al. (2018), which analyzed the impact of GHI variability on solar power generation across different regions.

2.2.1.2. Hydropower Energy Production

The energy produced by a hydropower plant can be expressed by the following equation:

$$E(t) = \rho * g * Q(t) * H * \eta \quad (4)$$

where: E'(t) is the energy produced at time t (in kWh), ρ is the density of water (in kg/m³), g is the acceleration due to gravity (in m/s²), Q(t) is the water flow rate at time t (in m³/s), H is the hydraulic head (in meters), and η is the efficiency of the hydroelectric system.

2.2.1.3. Wind Energy Production

As previously mentioned, wind energy production can be expressed by the following equation (Ayodele *et al.* 2012; Ayodele and Munda 2019; Rahmouni *et al.* 2017, Sulaeman *et al.* 2017; Lamboni *et al.,* 2024c):

$$E(t) = (1/2) * \rho * A * v^3(t) * \eta \quad (5)$$

where E(t) is the energy produced by the wind turbine at time t, and the other parameters are defined as follows: ρ is Air density (in kg/m³), A is Swept area of the turbine (m²), v(t) is Wind speed (in m/s at 90 meters from measurements taken at 10 meters) and, η is Efficiency of the wind turbine. The most common expression for the variation of wind speed with the height is the power law having the following form

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\alpha} \quad (6)$$

where v_2 and v_1 stand for the mean wind speeds at heights z_2 and z_1, respectively. The exponent α depends on factors such as surface roughness and atmospheric stability. Numerically, it lies in the range of 0.05–0.5, with the most frequently adopted value being 0.14 which is widely applicable to low surfaces and well-exposed sites (Lamboni *et al.* , 2024c).

Table 2 summarizes the key parameter values used in the hydroelectric (Eq. 4) and wind energy (Eq. 5) production equations for the Togolese context. These parameters include water and air density, flow rates, hydraulic heads, wind speeds, and system efficiencies. The proposed ranges, adapted to local conditions, provide a reliable framework for assessing Togo's renewable energy potential. The operational parameters for Eq. 4 (hydropower) and Eq. 5 (wind energy) are synthesized in Table 2. The proposed values, based on Togo's physical characteristics (including seasonal river flows and coastal wind patterns), cover densities (ρ), flow rates (Q), hydraulic heads (H), swept areas (A), wind speeds (v), and efficiencies (η), establishing a rigorous framework for renewable resource assessment. This table consolidates reference parameters for modeling renewable energy production in Togo (Lamboni *et al.,* 2024a). The hydropower data (Eq. 4) reflects characteristics of national watercourses, while wind parameters (Eq. 5) incorporate local wind measurements at 90 m height. These values, validated by Togolese energy authorities, serve as the basis for technical feasibility analyses.

2.2.1.4. Hydrogen Production Calculation

The production of hydrogen via hydro energy is based on using electricity generated by hydroelectric power plants to supply an electrolyzer. The electrolyzer breaks down water (H_2O) into oxygen (O_2) and hydrogen (H_2). This process, known as water electrolysis, uses electricity from hydropower to drive a chemical reaction (Zafar *et al.* 2023).

2.2.1.5. Battery State of Charge (SOC)

The state of charge (SOC) of the battery at any given time step is determined using the following equation:

Table 2
Parameter Values for Energy Production Equations

Equation	Parameter	Symbol	Value Range	Remarks
Hydropower (Eq. 1)	Water density	ρ	1000 kg/m³	Constant for fresh water
	Gravity acceleration	g	9.81 m/s²	Standard value
	Hydraulic head	H	10–100 m	Low-head (10–30 m) typical in Togo
	System efficiency	η	70–85% (0.7-0.85)	Includes turbine, generator, and pipe losses
Wind Energy (Eq. 2)	Air density	ρ	1.225 kg/m³	At sea level, 15°C
	Swept area	A	πR² (R: rotor radius)	-
	Turbine efficiency	η	30–45% (0.3-0.45)	Betz limit (59%) + mechanical losses

Table 3
Geographic Coordinates of Togo's Meteorological Stations

Main Meteorological Stations	Latitude (North)	Longitude (East)	Altitude (m)	Location Relative to Country
Lomé	06°10'	01°15'	19.60	South
Nangbeto	7⁰.43333 ''	0⁰.6333333"	117	South
Atakpamé	07°35'	01°07'	399.66	South
Blitta	8° 18' 60.00"	0° 58' 59.99"	304.48	North
Alédjo	9°15'0"	1°12'0"	613	North
Sokode	8° 58' 59.99"	*1° 07' 59.99"*	387	North

$$SOC(t+1) = SOC(t) \pm \left(\frac{P_{bat.\Delta t}}{capacity}\right).100 \qquad (7)$$

Where: Pbat is the power charged or discharged (W), Δt is the time interval (hours) and Capacity is the battery capacity (Wh).

Additionally, Hydrogen production (Rezaei et al. 2019) is estimated by the formulas as below:

$$H = \left(\frac{E_{out}}{E_{con}}\right) \bullet eff_{con} \qquad (8)$$

Where: H the amount of hydrogen produced [Nm^3], E_{out} the amount of wind, hydro or solar electricity [kWh], eff_{con} the performance of rectifier efficiency with the value of 95%, E_{con} the amount the energy consumption of 5 kWh/Nm^3 in the electrolyzer. Equation (7) is used to convert Nm^3 to weight [m] in kg (Rezaei *et al.* 2019)

$$m = N.m^3.\left(\frac{1mol}{0.022414Nm^3}\right).\left(\frac{0.002016kg}{1mol}\right) \qquad (9)$$

2.2.1.6. Electrolyzer (Hydrogen Production)

The mass of hydrogen produced by the electrolyzer is calculated using:

$$m_{H2} = \frac{P_{elec}.n_{elec}}{HHV_{H2}} \qquad (10)$$

Where: $n_{elec}$is the electrolyzer efficiency, $HHV_{H2}$is the higher heating value of hydrogen.

2.2.1.7. Fuel Cell (Power Generation)

The power generated by the fuel cell is given by:

$$P_{fc} = m_{H2}.n_{fc}.HHV_{H2} \qquad (11)$$

Where: n_{fc} is the fuel cell efficiency (~50%)

2.2.1.8. Power Balance

The power balance equation ensures the system meets the required load:

$$P_{load} = P_{tot} \mp P_{bat} + P_{fc} - P_{elec} \qquad (12)$$

2.2.2. Data Collection, Site Selection, Optimization and Simulation Tools

Solar radiation and wind speed data were sourced from meteorological stations, satellite databases (e.g., NASA POWER, ERA5), and national energy reports, while hydropower data from the Nangbéto Hydropower plant were also analyzed. Six cities in Togo, selected based on climatic diversity, are highlighted in Figure 1. Data on hydrogen production feasibility were gathered from scientific literature and case studies, while energy demand statistics were obtained from CEET and ARSE. Table 3 presents the selected study sites along with some of their key characteristics. To optimize hydrogen production from renewable sources, HOMER Pro, Python, and electrolyzer modeling were used. HOMER Pro assesses the techno-economic viability of hybrid energy systems, identifying cost-effective configurations (Connolly *et al.* 2010; Riayatsyah *et al.* 2022). Python enables system optimization through advanced algorithms, including machine learning and linear programming, enhancing energy flow analysis (Victor *et al.,* 2021; Abdellatif *et al.* 2024). Finally, electrolyzer modeling accounts for efficiency variations in hydrogen production. The integration of these tools significantly improves the design and performance of green hydrogen systems.

3. **Results**

3.1. Feasibility of Hydrogen Production Using Hydroelectric Energy from the Nangbeto Dam

This study explores the feasibility of hydrogen production using hydroelectric energy from the Nangbeto dam. Among six potential sites, Nangbeto was selected due to the availability of hydrological and energy data, which are essential for a rigorous analysis. The objective is to assess seasonal variations in water discharge, electrolysis efficiency, and potential hydrogen production. The analysis of the results obtained from various curves enables the identification of major trends in the evolution of key parameters influencing hydrogen production via electrolysis. The blue graph (Figure 3a) representing the variation in water discharge shows a strong seasonality. Specifically, the discharge remains low during the first months of the year, fluctuating between 10 and 20 m^3/s, before sharply increasing from May onwards. This increase reaches peak values exceeding 120 m^3/s between July and October, followed by a significant drop around November. This fluctuation aligns with the hydrological regimes observed in West African river basins, where the rainy season leads to a rapid rise in water levels. These results confirm the predominant influence of seasonal precipitation on water availability for both hydroelectric energy production and hydrogen generation. The green graph (Figure 3b) illustrates that the power potentially available for electrolysis fluctuates between 80 kW and 120 kW throughout the year. Unlike water discharge, power availability does not exhibit pronounced seasonality, although significant fluctuations are observed. This relative stability could be attributed to optimized management of hydroelectric energy or the presence of energy storage systems that mitigate abrupt discharge variations. When comparing these findings with ACE (2024) on a site in Southeast Asia, it is evident that hydraulic power can fluctuate more significantly when storage infrastructure is limited. In our case, improved regulation may explain the lower variability observed. The efficiency of the electrolyzer (purple graph in Figure 3c) ranges between 65%

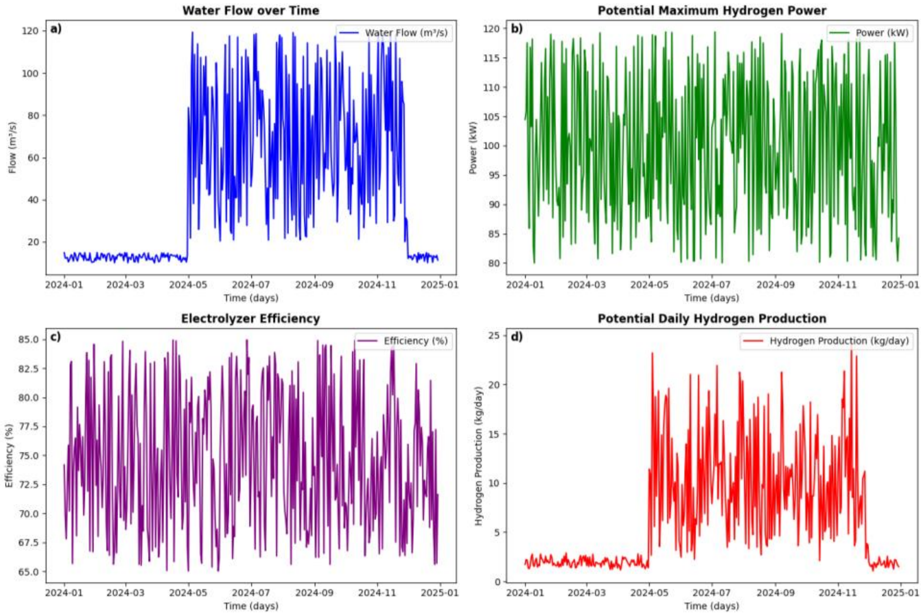

Fig. 3. Seasonal Variations in Water Discharge and Hydrogen Production Potential at Nangbeto Dam

and 85%, with notable oscillations. This behavior is typical of alkaline or Proton Exchange Membrane (PEM) electrolyzers, whose efficiency depends on several factors, including temperature, pressure, and the quality of the supplied electrical current. According to Bachir *et al.* (2019)**,** alkaline electrolyzers used in a similar project in Morocco demonstrated an average efficiency of 75%, with peaks reaching 85% under optimal conditions. These values align with our findings, suggesting that the performance of the studied electrolyzer is consistent with industrial standards. The evolution of daily hydrogen production (red graph in Figure 3d) directly reflects variations in water discharge. Low production is observed at the beginning of the year (below 5 kg/day), followed by a gradual increase starting in May, reaching peak values of approximately 25 kg/day between August and October. This pattern highlights the significant influence of water discharge on hydrogen production.

3.2. Hydrogen monthly production potential at Nangbeto based on Hydro-solar-wind energy

The analysis of the results presented in the graphs (Figure 4a) highlights the monthly variations in renewable energy production and their impact on hydrogen production. First, solar energy production remains relatively stable throughout the year, fluctuating between 30,000 kWh and 40,000 kWh. A slight increase is observed between March and May, followed by stabilization. This trend reflects the relatively constant availability of solar radiation, with minor seasonal fluctuations. Next, wind energy production remains lower than solar energy, ranging from 10,000 kWh to 18,000 kWh. A slight increase is noted during the summer months, particularly in July (around 17,000 kWh) and August (approximately 18,000 kWh). This suggests relatively stable wind conditions with a moderate seasonal increase. In contrast, hydroelectric production exhibits extreme variations. A significant increase is observed in August

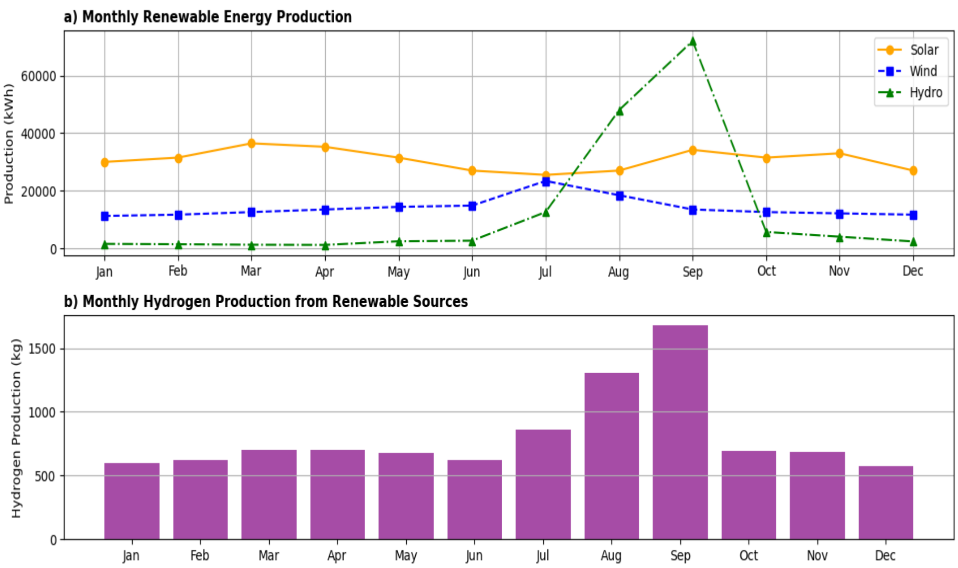

Fig 4. (a) Monthly production of renewable electricity (solar, wind, hydro); (b) Corresponding hydrogen production estimated via electrolysis at 70% efficiency.

(160,000 kWh), reaching a peak in September (approximately 240,000 kWh) before sharply declining in October. This pattern is likely influenced by seasonal rainfall and river flow variations, which strongly impact hydroelectric capacity. These energy production fluctuations directly affect hydrogen production, as shown in the second graph(Figure 4b). Hydrogen production remains relatively stable in the first and last months of the year, ranging from 500 kg to 750 kg. However, a gradual increase is observed from June (800 kg), peaking in September at approximately 1,700 kg. This peak coincides with the highest hydroelectric production, suggesting that hydropower plays a crucial role in overall hydrogen generation capacity. These results indicate that hydrogen production is maximized during periods of abundant hydropower generation. Nevertheless, this hybrid approach presents an interesting potential for energy management. By storing hydrogen during periods of high hydropower production (e.g., July to September), it could compensate for lower hydropower production during less favorable months, such as January to April. This makes hydrogen a form of energy storage that can be utilized both to stabilize the energy grid and meet future energy demands.

3.3. Seasonal Energy Balancing and Storage Dynamics at Nangbéto

The energy dynamics at Nangbéto showcase a seamlessly integrated system where renewable generation, hydrogen storage, and fuel cell utilization work in harmony, ensuring uninterrupted power supply and optimal efficiency throughout seasonal variations. The analysis of energy dynamics at Nangbéto (Figure 5) reveals a well-balanced system between renewable production, storage in the form of hydrogen, and energy restitution through the fuel cell. The evolution of energy parameters over the months highlights the system's adaptation to seasonal variations. The state of charge (SOC) fluctuates between 60% and 74%, indicating stable battery management. During the dry season, from November to April, a slight decrease in the average SOC is observed, reflecting an increased demand on reserves to compensate for the decline in renewable production. In contrast, during the wet season, from May to October, the surplus energy allows for maintaining a higher SOC, ensuring optimal battery recharge. In parallel, the fuel cell (P_fc) plays a key role in maintaining system balance, primarily activated during the dry season when energy demand is compensated by stored hydrogen. This energy transition ensures continuous power supply despite the seasonal fluctuations in renewable production.

Moreover, the analysis of combined hydroelectric, solar, and wind power production in Figure 6 highlights distinct seasonal trends. During the wet season, production is significantly higher due to abundant rainfall and favorable winds, with a particularly marked peak in August, when renewable energy reaches an optimal level. Conversely, during the dry season, production gradually decreases, making it necessary to rely on hydrogen stocks generated during the previous months. This complementarity between production and storage is essential to ensure energy continuity throughout the year. The smooth operation of the system relies on a well-defined interaction between different energy sources and storage devices. During the wet season, the surplus renewable energy maximizes hydrogen production through electrolysis. With an efficiency of 70%, the electrolyzer can generate up to 2,772 kg of H_2 in August, a sufficient amount to ensure future energy supply. This overproduction also helps maintain a high SOC, ensuring energy stability in anticipation of the dry season. When renewable production becomes insufficient, the system draws from hydrogen stocks to power the fuel cell. Thus, hydrogen consumption follows an inverse trend to renewable production, compensating for the decline in hydroelectric and solar energy. Although the SOC slightly decreases, it remains generally stable, proving the effectiveness of energy storage and management. The performance evaluation of the system highlights several key points, including a well-managed energy balance due to coordination between production, storage, and consumption, efficient use of technologies with a 70% efficiency electrolyzer and a 50% efficiency fuel cell, as well as enhanced energy autonomy with an estimated annual hydrogen production of 20,000 kg, covering a significant portion of energy needs during critical months.

The Table 4 summarizes the monthly energy flows and hydrogen production metrics for the solar-wind-hydro hybrid system at Nangbéto, highlighting seasonal variations and system performance. Hydropower fluctuates significantly, from 80,000 MWh in January to 220,000 MWh in August, following seasonal discharge trends. Solar and wind contributions remain stable, averaging 30–40 MWh/month and 10–18 MWh/month, respectively, reinforcing hydro's dominant role in the energy balance. Hydrogen production mirrors this pattern, with a minimum of 380 kg in January and a peak of 1,450 kg in August,

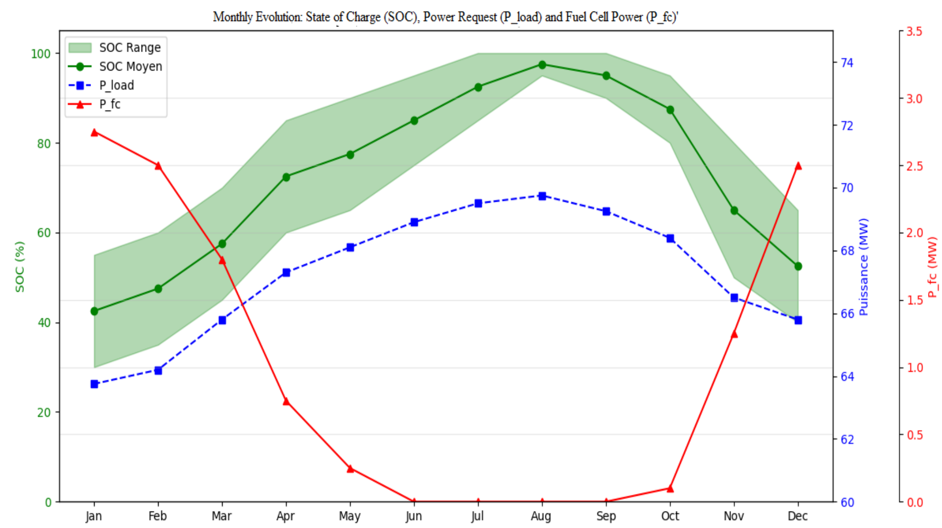

Fig. 5. The heat map shows the monthly values of four key parameters: SOC_min (minimum state of charge), P_load (power demand), P_fc (power supplied by the fuel cell), and H_2_prod (hydrogen production). Darker colors indicate higher values. High hydrogen production is observed between June and September, corresponding to a reduction in fuel cell utilization.

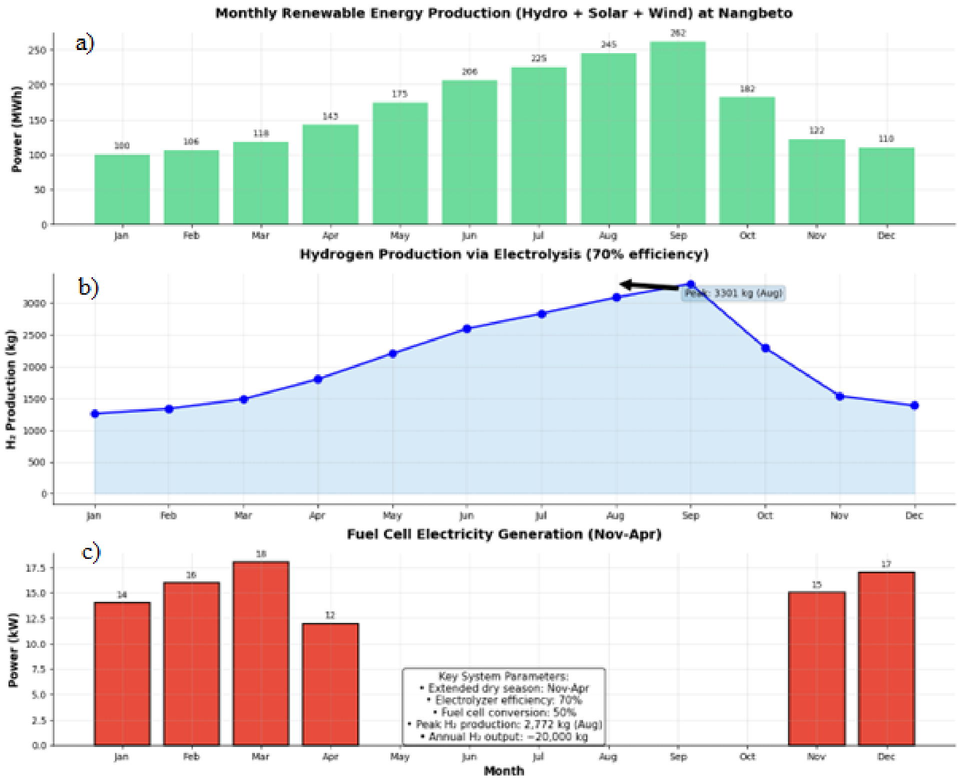

Fig. 6 Monthly Renewable Energy, Hydrogen Production, and Fuel Cell Electricity Generation in Nangbeto (Wet/Dry Season Dynamics)

reflecting surplus renewable energy. The battery's state of charge (SOC) fluctuates accordingly, dropping to 30–55% in January requiring fuel cell activation while reaching 95–100% in August, indicating surplus energy. April and November represent balanced conditions, with SOC ranging from 50–85%. Energy deficit coverage mechanisms demonstrate system resilience: in January, 78% of the shortfall is covered by stored hydrogen, while in April and November, battery discharge plays a greater role (92% and 85% coverage, respectively). The SOC drop to 30% in January highlights wind power intermittency, supporting the need to optimize turbine height (110m) for improved energy capture. These findings underscore the importance of strategic system adjustments to enhance reliability during low hydro periods. Moreover, the results presented in Table 5 indicate that the hybrid system employs a 2.75 MW fuel cell and a ±3 MW battery to balance the electrical load. This dynamic operation is validated by the monthly analysis in Table 4: in January, when hydropower generation is low (80,000 MWh), the fuel cell and the battery (SOC: 30-55%) cover 78% of the energy deficit. Conversely, in August, hydropower surplus (220,000 MWh) enables increased hydrogen production (1,450 kg) and a fully charged battery (SOC: 95-100%), eliminating any energy shortfall. These findings demonstrate the effectiveness of the hydro-hydrogen-battery coupling in ensuring a flexible and resilient energy management system.

Table 4.
Monthly energy flows and hydrogen production metrics for the solar-wind-hydro hybrid system at Nangbeto

Month	Hydro Power (MWh)	Solar PV (MWh)	Wind (MWh)	H_2 Production (kg)	Battery SOC Range (%)	Energy Deficit Coverage	Key Observations
January	80,000	12,300	8,400	380	30-55	78% (FC+H_2)	Low hydro, FC activation
April	120,000	14,100	9,200	620	60-85	92% (battery)	Balanced generation
August	220,000	13,800	10,500	1,450	95-100	100% (curtailment)	Peak hydro production
November	100,000	12,900	8,800	510	50-80	85% (battery)	Transition season

Table 5
Power Distribution and Balancing Components of the Hybrid Energy System

Aspect	Power Outputs	Monthly Analysis	Logical Connection
Fuel Cell (P_fc)	2.75 MW	380 kg (Jan) → 1,450 kg (Aug)	Activated during deficits (Jan) to supplement grid power; H_2 production scales with surplus (Aug).
Battery (P_bat)	±3 MW (charge/discharge)	SOC: 30% (Jan) → 100% (Aug)	Discharges (-3 MW) during low hydro (Jan); charges (+3 MW) during excess production (Aug).
Load Power (P_load)	63.75 MW (discharge) – 69.75 MW (charge)	Deficit coverage: 78% H_2 (Jan) → 100% curtailment (Aug)	Dynamically balances supply-demand: batteries and H_2 buffer seasonal variability.

3.4. Analysis of Wind Speed Characteristics Across Six Sites in Togo Variation of Wind Speed in selected Sites in Togo at 90 m height.

The analysis of wind characteristics across six sites in Togo, presented through the wind rose monthly wind speed data in meters per second (m/s), and monthly capacity factors in percentage, highlights the variations in wind direction, intensity, and energy production at different locations across the country. In addition, the Weibull distribution graph for each location based on the estimated shape (k) and scale (c) parameters is presented in this section.

The Weibull probability density function (PDF) provides a statistical representation of wind speed distribution, offering valuable insights into the feasibility of wind energy generation across different locations (Figure 7). The two key parameters shape parameter (k) and scale parameter (c) help assess wind stability and energy potential. Wind stability, represented by the shape parameter (k), plays a crucial role in determining the predictability of wind resources. Higher k-values (>3) indicate more consistent wind speeds, which enhance the efficiency of wind turbines. For instance, Atakpamé (k = 3.8) and Lomé (k = 3.5) exhibit relatively stable wind conditions, making them suitable for continuous energy production. In contrast, lower k-values (<2) signify greater wind intermittency, as observed in Nangbéto (k = 2.1) and Blitta (k = 2.5), which poses challenges for steady wind power generation. The scale parameter (c) represents the characteristic wind speed, influencing the overall energy output. Sokodé, with the highest c-value (6.8 m/s), confirms its potential for high-energy wind capture. However, its high turbulence (k = 5.82) may affect the operational efficiency of turbines, requiring robust designs to withstand gusty conditions.

Figure 8 illustrates the monthly variations in wind speed at a height of 90 m and the corresponding capacity factors for each site, highlighting the crucial relationship between these two parameters. Wind speed fluctuations directly impact the energy output of wind turbines, making it essential to analyze their seasonal trends and overall implications for wind energy generation. During the monsoon season (June to August), peak wind speeds are observed across most locations due to the strengthening of southwesterly monsoon winds. This phenomenon is particularly evident in coastal areas like Lomé and high-altitude regions such as Alédjo, where wind speeds reach their maximum values. Conversely, between November and February, wind speeds generally decrease across all sites,

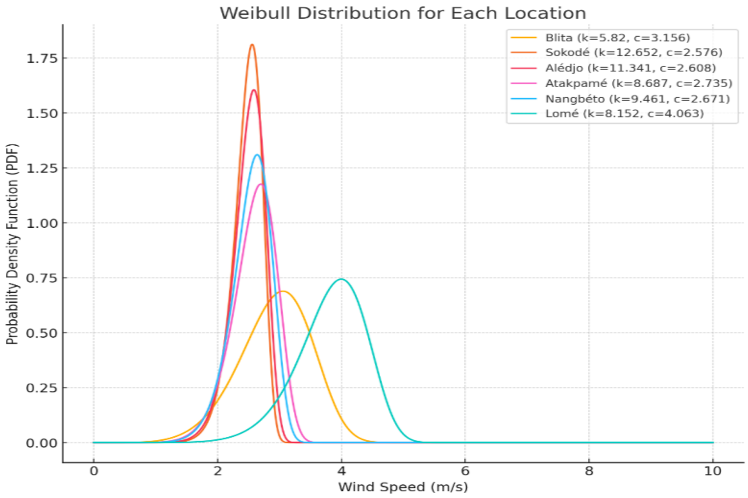

Fig. 7 Estimated Weibull parameters (k, c) for each location

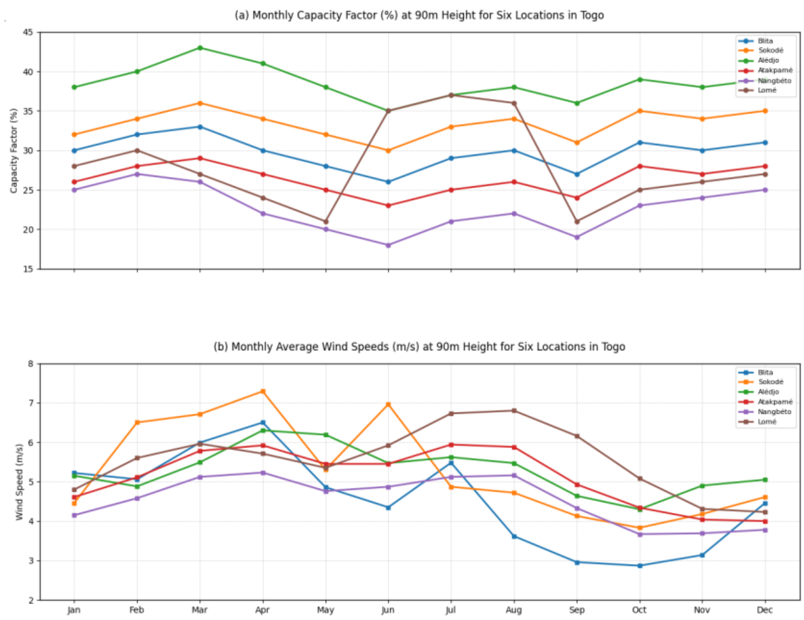

Fig. 8 Monthly Capacity Factors (%) and wind speed meters per second (m/s) at 90 m height

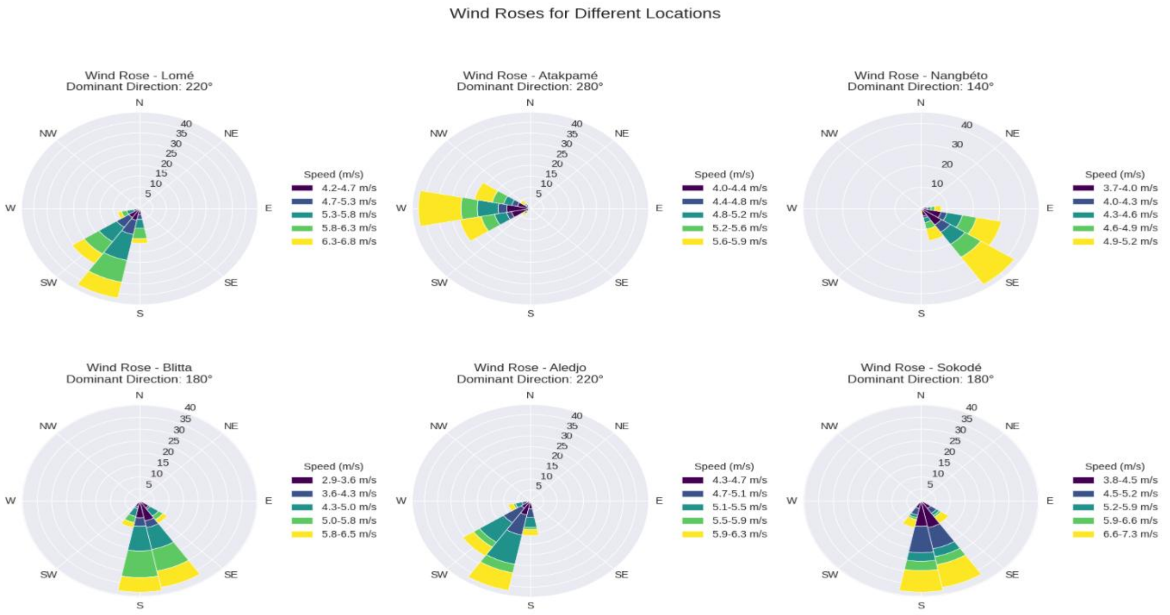

Fig.9 Wind Roses for Different Locations

coinciding with the dominance of dry Harmattan winds. Although these winds are present, their influence on wind power generation remains limited due to their lower intensity and seasonal inconsistency.

The variations in wind speed are directly reflected in the capacity factor, which follows a similar trend. Higher and more stable wind speeds result in increased energy production, as seen in Lomé (Lamboni *et al.* 2024c), where the capacity factor peaks at 37% in July when wind speeds reach 6.80 m/s. However, locations with lower wind speeds, such as Nangbéto, exhibit significantly lower capacity factors, averaging around 22%. This highlights the reduced feasibility of large-scale wind energy generation in such areas. A unique case is Sokodé, where wind speeds reach an impressive 7.29 m/s in April, the highest recorded among all sites. However, this potential is tempered by high turbulence, as indicated by a shape parameter (k = 5.82) in the Weibull distribution (Figure 7). Such high turbulence levels introduce operational challenges for wind turbine design and may affect the predictability of energy output. Overall, the interplay between wind speed, seasonal variations, and capacity factors underscores the importance of site-specific assessments for optimizing wind energy production. While some regions exhibit favorable conditions for large-scale wind energy deployment, others require specialized turbine designs or alternative energy strategies to compensate for wind intermittency and turbulence.

Figure 9 presents the wind rose diagrams, offering crucial insights into wind directionality and frequency across different sites. Understanding these patterns is essential for optimizing wind turbine orientation and maximizing energy capture. Wind direction varies significantly across regions, reflecting local climatic and topographic influences. In coastal areas such as Lomé, the predominant southwesterly winds (220° SW) result from maritime effects, providing a relatively stable wind flow throughout the year. Inland, the situation differs; Atakpamé experiences winds predominantly from the west-northwest (280° WNW), while Sokodé is characterized by southerly winds (180° S), suggesting a strong influence of orographic and convective processes. In contrast, Nangbéto exhibits weaker southeast-directed winds (140° SE), which further explains its lower wind potential compared to other sites. Seasonal variations play a crucial role in modifying wind direction and intensity. During the monsoon season (June–September), increased wind speeds are accompanied by slight shifts in prevailing wind directions, often tilting winds further southward. This seasonal reinforcement is particularly beneficial for regions like Lomé and Alédjo, where wind resources are already favorable. Conversely, during the dry Harmattan period (November–February), wind patterns shift, especially in northern areas, where stronger north-northeasterly winds occasionally emerge. This seasonal transition highlights the complex interplay between large-scale atmospheric circulation and local terrain effects, which must be carefully considered when planning wind energy installations. These findings underscore the importance of site-specific wind direction analyses in turbine positioning. While some regions experience stable and predictable wind flows, others are subject to significant seasonal variations, necessitating adaptive turbine designs to optimize energy production throughout the year.

3.5. Hydrogen production potential from wind power in Togo

The analysis of wind energy and hydrogen production across different sites in Togo reveals significant variations in output due to differences in wind speed (Table 6). Generally, wind power follows a cubic relationship with wind speed, meaning that even small increases in velocity result in substantial gains in energy generation.

This trend is particularly evident in Lomé, which, with the highest recorded wind speed of 5.6 m/s, produces the greatest amount of wind energy, approximately 5.2 GWh per year. In contrast, Blitta, with the lowest wind speed of 4.8 m/s, generates only 3.3 GWh annually. Consequently, regions with higher wind speeds exhibit greater potential for wind energy utilization. Beyond wind energy production, this disparity also extends to hydrogen generation. Since hydrogen production is directly linked to energy output, sites such as Lomé and Sokodé yield the highest amounts, reaching up to 988,000 Nm^3 per year. Meanwhile, Blitta and Nangbéto produce significantly less, highlighting the influence of wind availability on hydrogen generation capacity. Given these results, it is evident that sites

Table 6
The annual hydrogen production potential for different sites in Togo based on wind energy

Site	Wind Speed (m/s)	E_out (kWh)	H (Nm^3)	H (kg)
Lomé	5.6	5.2e3	9.88E2	89.0
Blitta	4.8	3.3e3	6.27E2	56.5
Atakpamé	5.1	4.0e3	7.60E2	68.5
Nangbéto	4.9	3.5e3	6.65E2	60.0
Sokodé	5.3	4.4e3	8.36E2	75.3
Alédjo	5.2	4.2e3	7.98E2	71.8

with moderate to high wind speeds are better suited for green hydrogen initiatives, while lower wind-speed locations may require additional energy sources to optimize production. In this context, the feasibility of wind-powered hydrogen production becomes a key consideration. While high-wind-speed locations present a promising opportunity for large-scale hydrogen production at a lower cost, regions with moderate wind conditions may need to integrate hybrid renewable systems such as a combination of solar and wind to enhance efficiency. Moreover, to fully capitalize on this potential, it is crucial to evaluate the economic viability of hydrogen production in each location, particularly in areas where wind energy alone may not suffice. Given these findings, a strategic approach to hydrogen production in Togo should focus on leveraging high-potential sites like Lomé and Sokodé as central hubs for large-scale development. At the same time, locations such as Blitta and Nangbéto could benefit from complementary renewable energy sources to improve their overall contribution. Furthermore, considerations regarding storage and transportation must be taken into account to ensure an efficient and cost-effective hydrogen supply chain. As a result, targeted investments, policy support, and technological advancements will be essential in optimizing the role of wind energy in the country's renewable energy landscape.

3.5. Hydrogen production potential for different sites in Togo based on solar energy

The analysis of hydrogen production potential across different sites in Togo, based on solar energy, reveals significant variations (Table 7). The electricity output derived from solar energy ranges from 29,876.3 kWh in Nangbéto to 33,942.0 kWh in Blitta, highlighting differences in solar irradiance and efficiency in energy conversion. These variations directly impact the hydrogen production potential, with Blitta exhibiting the highest yield at 5,912.30 Nm^3 (532.15 kg), while Lomé records the lowest at 5,423.03 Nm^3 (482.72 kg). A closer examination of the results shows that the sites with higher electricity output, such as Blitta and Alédjo, also demonstrate a greater capacity for hydrogen generation. This trend suggests that regions with increased solar radiation or better system efficiency can significantly enhance hydrogen production. Nangbéto, despite having one of the higher solar energy values (21,535.0 kWh), has a relatively lower electricity output (29,876.3 kWh), which in turn reduces its hydrogen production to 5,810.45 Nm^3 (520.26 kg). This discrepancy may be attributed to differences in system performance, temperature variations affecting photovoltaic efficiency, or localized atmospheric conditions.

From a strategic perspective, these findings emphasize the importance of selecting optimal sites for hydrogen production infrastructure. Given that hydrogen storage and distribution play a crucial role in sustainable energy planning, prioritizing regions with higher efficiency in electricity generation such as Blitta and Alédjo could enhance energy security and contribute to a more stable hydrogen supply chain. Additionally, integrating complementary renewable sources such as wind energy could further optimize production, particularly in sites where solar generation fluctuates seasonally. Overall, the results affirm the feasibility of hydrogen production from solar power in Togo, with significant potential for scalability. The observed differences underscore the need for further studies on energy system optimization, particularly in areas where electricity output is lower than expected despite high solar energy availability. Investing in improved photovoltaic technology, energy storage solutions, and hybrid renewable systems could further enhance the efficiency and sustainability of hydrogen production in the country.

3.6. Analysis of Wind and Solar Energy Potential in Six Sites in Togo: Complementarity and Prospects for Hybrid Systems

The analysis of wind and solar energy potential across six selected sites in Togo Lomé, Blitta, Atakpamé, Nangbéto, Sokodé, and Alédjo reveals significant spatial and seasonal variations in renewable energy availability. The graphs of Figure 10, and Table 8 illustrate the monthly variations in wind energy, solar energy, and total energy for each site, providing insights into their complementarity and the overall feasibility of hybrid renewable energy systems. In Lomé, wind energy exhibits a clear seasonal pattern, peaking in June-July (1.3×10^7 W) and December (1.2×10^7 W), while solar energy follows an inverse trend, reaching its highest levels in March-April (4.3×10^8 W) and October (4.2×10^8 W). This complementary nature suggests that an integrated hybrid system could ensure a more stable energy supply throughout the year, with the total energy remaining stable at around 3.7×10^8 W to 4.3×10^8 W. Moving to Blitta, the wind energy potential is moderate, with peaks in May (2.3×10^6 W) and December (2.2×10^6 W), whereas solar energy remains more stable, reaching its maximum in March-April (4.2×10^8 W) and October (4.0×10^8 W). Here, the total energy varies between 3.6×10^8 W and 4.3×10^8 W, indicating that wind energy plays a supporting rather than a primary role. Similarly, Atakpamé exhibits fluctuations in wind energy, with peaks in June (2.0×10^6 W) and December (1.9×10^6 W), while

Table 7
the annual hydrogen production potential for different sites in Togo based on solar energy:

Site	Annual Solar Energy (kWh)	Electricity Output (kWh)	Hydrogen Production (Nm^3)	Hydrogen Mass (kg)
Lomé	20,075.0	32,613.5	5423.03	482.72
Blitta	21,900.0	33,942.0	5912.30	532.15
Atakpamé	20,440.0	31,679.2	5511.88	493.60
Nangbéto	21,535.0	29,876.3	5810.45	520.26
Sokodé	20,805.0	32,744.9	5616.73	501.49
Alédjo	21,170.0	31,810.6	5714.59	513.37

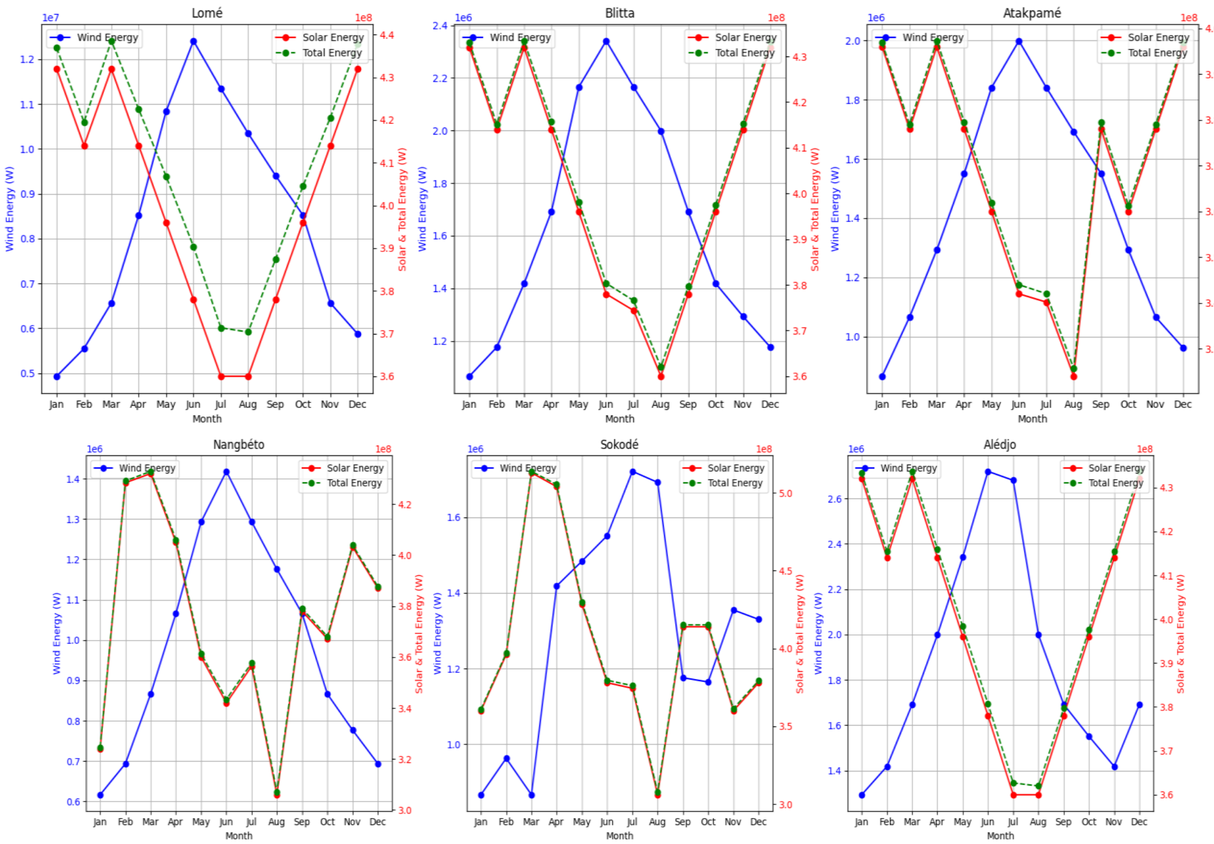

Fig 10. Monthly Variations of Wind, Solar, and Total Energy Potential in Six Sites in Togo

Table 8
Summary of Seasonal Variations and Complementarity of Renewable Energy Sources.

Site	Wind Energy Peak (W)	Solar Energy Peak (W)	Minimum Wind Energy (W)	Minimum Solar Energy (W)
Lomé	~1.3 × 10^7 (June-July)	~4.3 × 10^8 (March-April)	~0.5 × 10^7 (Jan)	~3.7 × 10^8 (June-July)
Blitta	~2.4 × 10^6 (June-July)	~4.2 × 10^8 (March-April)	~0.7 × 10^6 (Jan)	~3.6 × 10^8 (June-July)
Atakpamé	~2.6 × 10^6 (June)	~4.0 × 10^8 (March)	~0.8 × 10^6 (Jan)	~3.3 × 10^8 (June-July)
Nangbéto	~1.4 × 10^6 (June)	~4.2 × 10^8 (March)	~0.6 × 10^6 (Jan)	~3.0 × 10^8 (June-July)
Sokodé	~1.6 × 10^6 (June)	~4.5 × 10^8 (March)	~0.9 × 10^6 (Jan)	~3.2 × 10^8 (June-July)
Alédjo	~2.6 × 10^6 (June)	~4.3 × 10^8 (March)	~0.7 × 10^6 (Jan)	~3.6 × 10^8 (June-July)

solar energy follows a more moderate variation, peaking in March (4.0 × 10^8 W) and October (3.9 × 10^8 W). The total energy in this site ranges from 3.3 × 10^8 W to 3.9 × 10^8 W, highlighting solar energy as the dominant source. Shifting attention to Nangbéto, this site presents an interesting case with notable increases in wind energy in March (1.4 × 10^6 W) and June (1.3 × 10^6 W), while solar energy peaks in April (4.2 × 10^8 W). The alignment of these peaks suggests strong potential for combined energy production, although seasonal fluctuations may necessitate energy storage solutions. In Sokodé, wind energy shows pronounced variations, reaching peaks in May (1.6 × 10^6 W) and December (1.5 × 10^6 W). Unlike the other sites, wind energy in Sokodé experiences more irregular fluctuations, particularly between July and September, where values drop significantly. Meanwhile, solar energy remains relatively stable, peaking in March (4.5 × 10^8 W). The total energy fluctuates between 3.3 × 10^8 W and 4.5 × 10^8 W, reinforcing the crucial role of solar energy in maintaining stability. Finally, Alédjo exhibits strong complementarity between wind and solar energy, with wind energy peaking in June-July (2.6 × 10^6 W) and December (2.5 × 10^6 W), while solar energy reaches maximum levels in March (4.3 × 10^8 W) and October (4.2 × 10^8 W). As a result, total energy varies between 3.6 × 10^8 W and 4.3 × 10^8 W, further emphasizing the potential for hybrid systems. Overall, the results highlight the importance of site-specific energy planning, as each location presents unique seasonal dynamics. Lomé and Alédjo demonstrate strong complementarity between wind and solar resources, making them ideal candidates for hybrid renewable energy systems. In contrast, Nangbéto and Sokodé, despite having wind energy potential, show significant fluctuations, necessitating energy storage solutions. These findings suggest that hybrid energy systems could significantly enhance energy reliability, reinforcing the need for further studies on optimizing energy storage and grid integration strategies to maximize the benefits of these renewable energy resources.

4. Discussion

4.1. Comparison with other studies and Contribution for Renewable energy developments

This comparative analysis examines green hydrogen production potential in Togo against international benchmarks, highlighting how varying renewable energy strategies, technical constraints, and economic approaches shape outcomes across different geographical contexts (Table 9). The feasibility of

Table 9
Summarizing the feasibility of hydrogen production in Togo vs. other regions (Mauritania, China, Balkans)

Aspect	Togo	Other Regions (Mauritania, China, Balkans)
Hydropower Integration	• Seasonal fluctuations managed via hybrid systems (hydro + solar/wind). • Produces 5–25 kg H_2/day. • Relies on battery storage.	• Balkans (Schmitz *et al.,* 2023): Similar seasonal challenges, storage solutions. • China (Yang *et al.,* 2024): Grid-balancing reduces excess power (38.6% → 10.3%). Uses grid as storage.
Wind Energy	• Best site: Alédjo (Cf = 38%). • Low wind speeds (3–6.5 m/s). • Lomé produces ~37 tH_2/year (2.5 MW system). • High LCOH due to intermittency.	• Mauritania: Higher winds (7–9 m/s), Cf = 57.73%. • Produces 412 tH_2/year (4 MW turbine). • Lower energy-to-H_2 ratio (50 kWh/kg vs. Togo's 55 kWh/kg).
Solar Energy	• High irradiance in Blitta/Alédjo boosts H_2 production. • Hybrid systems needed for stability. • Nangbéto underperforms due to local conditions.	• Saudi Arabia (Al-Sharafi *et al.,* 2017): High irradiance = higher H_2 yields. • East Asia (Li *et al.,* 2023): Similar atmospheric challenges.
Economic Strategies	• Subsidies for hybrid systems.	• China: Mandates enforce renewable consumption. • Mauritania: Lower LCOH from stable wind resources.
Key Challenges	• Turbine inefficiency (cut-in speed >3.5 m/s). • Intermittency requires hybrid systems.	• Balkans/SE Asia: Seasonal hydropower variability. • Global: Storage integration critical (Dörenkämper *et al.,* 2020).
Solutions Proposed	• Optimize turbine selection (cut-in <3.5 m/s). • Hydro-solar-wind hybrids + storage.	• Grid-balancing (China). • Wind-solar hybrids (Mauritania, Iqbal *et al.,* 2019).

hydrogen production in Togo using hydroelectric, wind, and solar energy presents significant potential but also highlights challenges that are consistent with findings from similar research in different regions. The integration of seasonal hydropower variability with hydrogen production, as demonstrated in this study, mirrors result from previous research conducted in places like Norway, Sweden, and the Balkans. For instance, Schmitz *et al* 2023, in the Balkans emphasize the importance of managing seasonal fluctuations in hydropower to ensure consistent hydrogen output. In both contexts, energy storage and hybrid systems are vital to smooth out these fluctuations. In Togo, integrating storage batteries into hybrid systems (solar, wind, and hydroelectric energy) is crucial for managing the intermittency of renewable energies and ensuring stable hydrogen production. Specifically, the combination of low wind speeds and intermittency in the production of hydro turbines presents a major challenge. Batteries allow excess energy generated during periods of high production (such as on sunny days, wind energy peaks, or high flow during rainy seasons) to be stored and released when production is insufficient, particularly during periods of low wind, dry seasons, or low sunlight. This effective energy flow management ensures the continuity of green hydrogen production, even under less favorable weather conditions.

The results of this study suggest that a hybrid system based on hydropower, solar and wind energy, and hydrogen storage could offer a robust solution for energy management in Togo, with hydrogen storage potential to offset seasonal variations in hydropower production. These findings also highlight the need to better integrate these various energy sources and storage technologies into energy systems to maximize reliability and sustainability in energy supply. Batteries help mitigate the natural fluctuations related to wind and solar energy by storing the excess for later use. Therefore, this storage solution plays a fundamental role in reducing the impact of seasonal and weather-related variations on hydrogen production. This approach has been explored in research from Southeast Asia, where hydro-solar hybrid systems are implemented to enhance energy reliability (Iqbal et al., 2019). In the context of China, Yang *et al.* (2024) investigated a similar strategy, focusing on grid dependency reduction and achieving a 3,347-kWh reduction in excess power. The comparative analysis examines the approaches taken in Togo and Kuqa (China), focusing on system design, technical performance, economic implications, and climate adaptation strategies to identify key insights for future hydrogen development. While both regions adopt hybrid renewable hydrogen systems, they optimize them differently based on resource availability and infrastructure constraints. Togo integrates hydropower to manage seasonal discharge fluctuations, whereas Kuqa's strategy, as reported by Yang *et al.* (2024), emphasizes grid-balancing to improve system efficiency. Technically, our study found that Togo produces 5–25 kg/day of hydrogen, leveraging hydropower to stabilize solar/wind fluctuations, while Yang *et al.* (2024) reported that Kuqa reduced excess power from 38.6% to 10.3% through grid-balancing. Togo relies on battery storage, whereas Kuqa utilizes the grid as storage. Economically, Togo's subsidies support hybrid adoption, while China's mandates enforce renewable consumption.

Additionally, the wind energy potential in Togo, particularly in Lomé, Alédjo and Sokodé, aligns with findings from studies in coastal regions across Africa and Europe (Acar *et al.* 2014, Nnabuife *et al.*2 023). In Togo, wind power output is highly sensitive to local wind speeds (Lamboni *et al.* 2024), a pattern also observed in Morocco, Egypt and Mauritania (Reda *et al.,* 2022, Maaloum *et al.,* 2024), where modest increases in wind speed significantly boost energy production. For example, the techno-economic feasibility of wind-powered green hydrogen production in Mauritania (Maaloum *et al.,* 2024) and Togo (current study), highlighting key differences in capacity factors, turbine performance, and hydrogen yields. Wind energy performance varies considerably between Mauritania and Togo, driven by differences in wind speed regimes and turbine suitability. Mauritania benefits from higher average wind speeds (7–9 m/s), leading to a maximum capacity factor (Cf) of 57.73%, whereas Togo's best-performing site, Alédjo, reaches a capacity factor of 38%. A key factor behind this difference is the turbine cut-in speed. Mauritania's Goldwind 3.0 MW turbine, with a low cut-in speed of 2.5 m/s, efficiently harnesses moderate winds, maintaining a high Cf even at lower wind speeds. In contrast, Togo's lower wind speeds (3–6.5 m/s) constrain performance, with Nangbéto recording the lowest Cf (22%) despite optimal siting. These findings underscore the need for optimized turbine selection in Togo, with a focus on models that feature low cut-in speeds (<3.5 m/s) to improve efficiency. The disparity in wind resources directly impacts green hydrogen production potential. In Mauritania, sites like Nouadhibou leverage high-capacity factor values, producing up to 412 tH_2/year with a 4 MW turbine. In contrast, Togo's best site, Lomé, produces only approximately 37 tH_2/year with a 2.5 MW system. The energy-to-hydrogen conversion ratio further emphasizes this contrast: Mauritania's sites operate at about 50 kWh/kgH_2, benefiting from more stable wind conditions, whereas Togo's sites require approximately 55 kWh/kgH_2 due to wind intermittency and lower speeds.

For solar energy, this study reveals that higher solar irradiance in areas like Blitta and Alédjo leads to greater hydrogen production, which is consistent with findings from regions with similar climates, such as parts of West and East Africa. Comparative studies, such as Al-Sharafi *et al* (2017) in Saudi Arabia, have shown that areas with higher solar potential naturally contribute more to renewable hydrogen production. In particular, the study in Togo points out that regions with optimal solar irradiance combined with high efficiency in photovoltaic systems can lead to higher yields. However, in places like Nangbéto, despite favorable solar radiation, performance issues or local atmospheric conditions could limit energy production, a challenge also noted in solar energy studies from East Asia (Li *et al.,* 2022). The study's findings support the need for a hybrid approach in Togo, particularly combining wind and solar energy in areas where wind speeds are moderate, like Blitta and Atakpamé. This approach is in line with strategies discussed in global studies on hybrid renewable systems, which advocate for the combination of intermittent renewable sources to create a more stable and reliable energy grid (Iqbal *et al.,* 2019). Furthermore, integration of storage systems to balance the fluctuations in renewable energy generation has been emphasized in similar projects in Africa, Asia and Europe, which face similar challenges in stabilizing intermittent energy sources (Dörenkämper *et al.,* 2020, Fopah-Lele *et al*., 2021; Koleva *et al.,* 2021; Mokhtara *et al.,* 2021; Touili *et al*., 2018).

4.2. Limitations and future studies

While this study provides valuable insights, it is essential to acknowledge limitations that could influence the interpretation and applicability of the findings. Although six locations were strategically selected to represent Togo's diverse climatic conditions, the study does not capture all microclimatic variations across the country. Expanding future research to include a broader range of sites would provide a more comprehensive assessment of renewable energy potential. Another key limitation lies in the temporal scope of the data. The study relies on specific time periods, which may not fully account for long-term fluctuations in wind, water and solar energy availability. Incorporating multi-year datasets and seasonal variations would improve the reliability of predictions and better assess the long-term sustainability of hybrid renewable systems. While the study presents a techno-economic analysis, it does not comprehensively address the financial barriers to large-scale implementation. Infrastructure costs, investment requirements, and policy incentives play a crucial role in determining project viability. Future research should integrate a more detailed financial analysis to provide actionable recommendations for policymakers and investors. In addition to technical performance, successful deployment of renewable energy projects depends on environmental and social factors. Land-use impacts, community acceptance, and grid integration challenges remain underexplored in this study. Addressing these aspects through stakeholder engagement and environmental impact assessments would strengthen the feasibility of proposed solutions. A final limitation concerns the effect of temperature on system efficiency, particularly in photovoltaic (PV) and hydrogen production processes. Elevated temperatures can reduce PV efficiency and accelerate cell degradation, ultimately affecting hydrogen yields. These limitations highlight the need for further research to refine data collection, enhance modeling approaches, and address real-world challenges in deploying hybrid energy systems across in Togo (West-Africa). By expanding geographic coverage, improving temporal analysis, and integrating economic and social dimensions, future studies can provide more robust insights into the feasibility and sustainability of renewable energy solutions.

5. Conclusion

This study highlights the significant potential of hybrid solar-wind-hydrogen energy systems in Togo, emphasizing the feasibility of integrating diverse renewable energy sources for sustainable hydrogen production. The combination of hydroelectric, solar, and wind resources, each with varying regional potential, demonstrates that optimized energy management can ensure consistent hydrogen production despite seasonal fluctuations. The seasonal variations in hydroelectric discharge (from 10–120 m^3/s), alongside solar (29,876.3–33,942.0 kWh) and wind energy (with a range of 5.2–3.3 kWh in Lomé and Blitta), reveal the key role of each resource in influencing hydrogen production. Monthly energy flow analysis at Nangbéto indicates that hydro power production varies significantly, peaking at 220,000 MWh in August, which correlates with the highest hydrogen production (1,450 kg) in the same period. Battery storage systems are crucial in stabilizing energy production, with the system efficiently covering energy deficits in low hydro availability months, particularly in January, when 78% of the deficit is met through hydrogen-to-power conversion. The findings suggest that Blitta and Alédjo are ideal locations for hydrogen infrastructure, offering optimal solar and wind conditions, while Sokodé and Atakpamé present promising options for hybrid wind-solar systems. To fully leverage Togo's renewable energy potential, the study underscores the importance of energy storage solutions, hybrid integration, and targeted policy support to optimize the green hydrogen production and supply chain. These strategies are essential to ensuring a sustainable and reliable energy future for Togo, capable of addressing both current and future energy demands.

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