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Spatiotemporal Assessment of Wind–Solar Resources for Hybrid Renewable Electrification in Western Burundi

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ABSTRACT

Burundi continues to face persistent electricity shortages due to limited generation capacity and strong dependence on climate-sensitive hydropower resources. This study aims to quantify wind and solar energy potential in western Burundi, assess their seasonal complementarity, and evaluate the feasibility of PV–wind hybrid systems for rural electrification. Long-term datasets from the Burundi Geographical Institute (2013–2020 for wind; 1977–2017 for sunshine duration) were analyzed using statistical and empirical models. Wind resources were assessed through monthly distributions, directional frequency, and wind power density (WPD), while solar potential was estimated using the Ångström–Prescott model, suitable for data-scarce contexts. Results indicate mean annual solar irradiance of ~5.3 kWh/m²/day (~1,930 kWh/m²/year) with modest seasonal variation (±10%), supporting reliable year-round PV generation. Wind exhibits strong seasonality, peaking at ~160 W/m² (Class 3) between June and October but averaging ~60 W/m² annually (Class 2), limiting standalone potential. These findings demonstrate how the complementary nature of wind and solar regimes can strengthen rural mini-grids and reduce vulnerability to hydrological variability. The study provides new evidence to guide renewable-energy planning and support progress toward universal energy access in Burundi.

Keywords: Renewable energy; WPD; solar irradiance; hybrid systems; Burundi, SDG7

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1. INTRODUCTION

Burundi faces persistent challenges in providing modern, reliable electricity: national access remains very low and rural electrification is especially limited, which constrains economic activity and wellbeing across the country. Recent national statistics place electricity access at around 11–12% of the population (with rural access substantially lower), underscoring a large connectivity gap that persists despite ongoing policy efforts (African Development Bank, 2024; IRENA, 2023; Mellaku et al., 2025).

The country's generation mix remains heavily dependent on hydropower, which historically accounted for the vast majority of installed capacity (Manirambona et al., 2022; Nsabimana, 2020). Aging infrastructure, sedimentation, and reduced river flows during droughts have repeatedly undermined hydropower output, producing frequent supply shortfalls and raising the cost and vulnerability of the national system. At the same time, modest additions of thermal generation and the recent commissioning of the 7.5 MW Mubuga solar plant have begun to diversify supply, but overall capacity and resilience remain insufficient for national needs (IRENA and AfDB, 2022; Jeff Felten, Yara Akkari, 2023). These constraints are compounded by macroeconomic pressures. According to World Bank data, Burundi's GDP per capita (constant prices) has steadily declined in recent years, which limits consumers' ability to afford electricity and constrains national investment in large-scale energy infrastructure (World Bank Group, 2024). While population growth increases demand, electricity in Burundi functions as a normal good: higher incomes would stimulate greater demand. The decline in real incomes therefore represents a national challenge and a limitation for demand forecasting, necessitating decentralized, low-cost electrification approaches (United Nations, 2024).

Given these conditions, decentralized renewable energy systems—especially solar PV and wind—offer a viable pathway to improve energy access while reducing dependence on vulnerable hydro-power. Solar resources in Burundi are spatially consistent, and wind patterns, although modest annually, exhibit clear seasonal peaks in western lowlands near Lake Tanganyika (Bashahu et al., 2022; Bashahu & Ndacayisaba, 2024). This temporal complementarity supports the design of hybrid PV–wind systems, which can reduce storage requirements, improve mini-grid reliability, and enhance resilience.

Globally, the case for hybrid mini-grids has strengthened significantly. Since 2010, the costs of solar PV, wind power, and battery storage have fallen by 60–90%, driven primarily by large-scale manu-facturing and deployment in China, the United States, and India (Muyi Yang & Sam Butler-Sloss, 2025). In India, solar farm CAPEX is now comparable to new coal-fired power stations, confirming the competitiveness of renewables in emerging economies (IRENA, 2025). Furthermore, practical experiences—such as Puerto Rico's expanding micro-grid deployments built to withstand extreme weather—demonstrate that decentralized renewable mini-grids can enhance energy security, resilience, and climate adaptation (Gurbanov, 2024). These examples offer valuable insights for countries like Burundi seeking robust alternatives to mini-grids expansion.

The introduction should briefly place the study in a broad context and highlight why it is important. It should define the purpose of the work and its significance. The current state of the research field should be reviewed carefully and key publications cited. Please highlight controversial and diverging hypotheses when necessary. Finally, briefly mention the main aim of the work and highlight the principal conclusions. As far as possible, please keep the introduction comprehensible to scientists outside your particular field of research.

2. LITERATURE REVIEW

Burundi faces persistent energy access challenges, with electrification rates among the lowest in sub-Saharan Africa. As a result, various studies have investigated the country's renewable energy potential-particularly solar and wind-as viable alternatives to the existing hydropower-dominated system. These studies provide essential insights into resource availability, system design, and the technical-economic feasibility of renewable energy deployment.

Several investigations have focused on the solar energy potential in Burundi. (Lawin et al., 2019) analyzed historical data on solar irradiance and temperature variation across the country and found favorable conditions for photovoltaic (PV) deployment, especially during the dry season. Their findings revealed that most regions receive average solar irradiance values suitable for off-grid PV systems. Complementarily, (Niyongendako et al., 2020) assessed the projected impact of climate change on PV performance using RCP 8.5 scenarios. Their modeling results suggested a minor decline in irradiance—by approximately 2 to 4 W/m^2 by 2050—but not significant enough to hinder future PV investments. These results validate the long-term viability of solar energy development, even under shifting climate patterns.

Wind energy potential has also garnered attention in recent years. (Bashahu et al., 2022) evaluated wind resources at two sites—Bujumbura and Muyinga—using hourly wind speed data. Applying Weibull statistical modeling, the study concluded that Bujumbura has favorable wind regimes for medium-scale wind power applications, particularly at higher altitudes. Similarly, (Placide et al., 2021) examined wind characteristics in four locations, including Gitega, Gisozi, Mpota, and Bujumbura. Their analysis confirmed that Bujumbura exhibits the highest wind power density, reinforcing its potential for wind energy development. These findings are further supported by (Placide & Lollchund, 2024a), which assessed the reliability of the Weather Research and Forecasting (WRF) model in simulating wind data in Burundi. The study reported that mean wind speeds between 4 and 9.7 m/s at 12 meters height were observed during the dry season, indicating suitability for micro-wind or small-scale wind turbines in specific regions, particularly in the west.

Moreover, environmental and spatial considerations have been increasingly integrated into energy planning (Placide & Lollchund, 2024b) employed fuzzy logic and GIS-based multi-criteria analysis to identify optimal wind farm locations in Burundi. The analysis found that Burundi western region where wind speeds exceed 5 m/s at 12 m height is well suited for the installation of commercial wind turbines.

Collectively, these studies underline Burundi’s considerable potential for renewable energy development, with strong resource availability for both solar and wind applications. While solar energy has seen increasing deployment—including the commissioning of the $7.5MW$ Mubuga Solar Power Station (REPP, 2025)—and wind assessments have been conducted at several locations, the research remains largely segmented.

Most previous studies in Burundi have examined solar and wind resources separately, and they have generally been site-specific, without assessing the seasonal complementarity between these resources for hybrid energy planning. Globally, hybrid renewable energy systems—particularly PV–wind combinations—are known to enhance supply reliability and reduce storage requirements by leveraging seasonal complementarity (Ayua & Emetere, 2024). In Burundi, however, the lack of integrated assessments of long-term wind–solar dynamics limits the evidence needed to design cost-effective hybrid mini-grids for rural electrification and to reduce reliance on hydropower. This gap is especially pronounced in the western region, where solar irradiance remains consistently high, and wind resources, although modest on average, occasionally reach favorable levels during the dry season. The temporal complementarity of these resources indicates that integrated wind–solar systems could provide more stable energy supply than single-source systems (Bashahu & Ndacayisaba, 2024; Placide et al., 2021; United Nations, 2023).

Beyond Burundi, several recent international studies provide broader insights into clean-energy dynamics that are directly relevant to hybrid-system planning. Daily-based analyses have shown that nuclear and renewable electricity generation substantially decrease CO_2 emissions in major nuclear-producing countries, illustrating the environmental benefits of expanding clean-energy portfolios (Kartal, Pata, et al., 2023). Recent empirical work using asymmetric causality methods demonstrates that nuclear and renewable energy consumption interact in nonlinear, country-specific ways — for example, in South and Southeast Asia, where long-run and shock-based effects differ significantly across countries. Econometric investigations using bootstrap-rolling-window techniques in G7 countries continue to show that renewable energy adoption supports both economic growth and environmental quality (Akduğan & Pehlivan, 2025). Other studies using quantile regression approaches reveal asymmetric displacement relationships between major clean-energy types, suggesting that renewable electricity may substitute for other sources more strongly under specific conditions.

Frequency-domain causality analysis further reveals that relationships among renewables, CO_2 emissions, and economic growth vary across time scales: symmetric and asymmetric spectral Granger causality tests in the U.S. show distinct permanent and temporary bidirectional causality patterns (Kartal, Ghosh, et al., 2023; Kartal, Mukhtarov, et al., 2025). Finally, wavelet-quantile analyses show that energy productivity and resource productivity have quantile- and scale-specific negative effects on CO_2 emissions - for instance, recent evidence from France indicates that productivity gains can reduce emissions more strongly at higher quantiles and over longer horizons (Kartal, Depren, et al., 2025). These findings together underscore the value of integrated, multi-horizon planning when designing hybrid clean-energy systems (Kirikkaleli & Agyemang, 2025; Zuhal & Göcen, 2024).

Regional sustainability and energy-access research also supports the case for decentralized renewable energy in contexts similar to Burundi, emphasizing the importance of resource variability assessment, feasibility analysis, and hybrid-system optimization (BARIKUNDA & UFITEYEZU, 2025; Eze et al., 2024). These studies generally converge on the conclusion that solar and wind resources, when jointly assessed, offer significant opportunities for improving energy access and reducing dependence on climate-sensitive hydropower.

Despite this growing body of literature, existing research on Burundi remains largely fragmented. Most solar and wind assessments have been conducted independently and are often site-specific, without providing a comprehensive analysis of the seasonal complementarity between these two resources. This gap is notable given global evidence that hybrid PV–wind systems can significantly enhance reliability and reduce storage needs by leveraging temporal complementarities. In western Burundi, solar irradiance is consistently high throughout the year, while wind potential, although modest on an annual basis, strengthens considerably during the dry season—indicating a natural synergy that has not been fully explored.

The structure of a literature Review can be in one of the following styles: Author (year) investigated the problem in which period, in the case of which country, using which theoretical approach, which method, and what results were obtained. Grouping studies according to the theoretical or empirical results obtained, or according to the used method or theory/concept.

3. METHODS

3.1. Area of Study

Burundi is a small, landlocked country in East Africa, sharing borders with Rwanda to the north, Tanzania to the east and south, and the Democratic Republic of the Congo to the west (Fig. 1). With a population exceeding 13 million, Burundi remains one of African's most densely populated and least urbanized countries (World Bank, 2025).

The country's topography, as illustrated in Fig. 1, consists mainly of central plateaus, hills, and flat plains, forming part of the eastern flank of the Western Rift Valley. Elevations range from approximately 770 meters to 2,684 meters above sea level. The country is commonly divided into four major topographical regions: the low-lying Imbo Plain, the elevated Congo-Nile Ridge, the extensive Central Plateaus, and the gently sloping depressions in the east and northeast (Ekanem & Singh, 2024; Heckmann et al., 2016). The western lowlands adjacent to Lake Tanganyika, boasts unique geographical and climatic features, making it as a key area for renewable energy resource assessment, especially for wind and solar technologies.

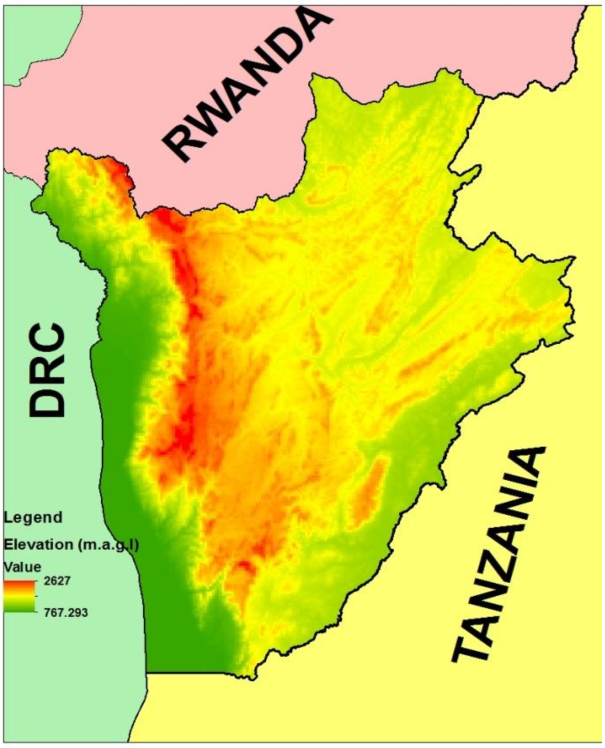

Fig. 1 Burundi topography map (DIVA-GIS, 2025)

3.2. Data collection and preprocessing

This study used two long-term meteorological datasets from the Burundi Geographical Institute (IGEBU): daily wind speed (2013–2020) and sunshine duration (1977–2017) recorded at the Bujumbura airport station. Both datasets underwent standard quality control, including detection and correction of missing values, outliers, and non-climatic shifts caused by station relocation or instrument changes (Bashahu et al., 2022; Niyongabo et al., 2023; Niyongendako et al., 2020).

The Penalized Maximal T (PMT) and Penalized Maximal F (PMF) tests, widely used in climatology to detect undocumented mean shifts in time series (Domonkos, 2024; Squintu et al., 2020), were jointly applied because they complement each other: PMT is more effective for identifying abrupt shifts in stable series, whereas PMF is better suited to series with linear trends. Their combined application enhances detection accuracy, reduces false alarms [35–38], and produces reliable, continuous records suitable for long-term wind–solar variability assessment in western Burundi (Xu et al., 2025).

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Both the Penalized Maximal T (PMT) and Penalized Maximal F (PMF) tests were used because they complement each other: PMT detects abrupt mean shifts in stable series, while PMF performs better in series with linear trends. Using both improves detection accuracy and minimizes false alarms (Capozzi et al., 2020; Feng & Wang, 2021; He & Wang, 2020; Zhou et al., 2022), resulting in reliable, continuous records suitable for long-term wind–solar variability assessment in western Burundi.

3.3. Solar radiation estimation

Solar irradiance was calculated using the Angström-Prescott model, a widely adopted empirical method that estimates monthly average daily global horizontal irradiation (GHI) from sunshine duration. The Ångström–Prescott (A–P) model was selected because it is specifically designed for sunshine-duration data—the only continuous long-term record (1977–2017) available for the study region. Modern satellite- or ANN-based models require high-resolution inputs such as aerosol optical depth, cloud fraction, or sub-hourly radiation data that are unavailable for this historical period.

The A–P approach, recommended by the WMO (WMO (World Meteorological Organization), 2008), has been widely validated in similar tropical and sub-Saharan contexts (Deng et al., 2025; Iradukunda & Chiteka, 2023; Vernet & Fabregat, 2023) and typically yields monthly-mean GHI estimates within ±5–10% uncertainty (Asilevi et al., 2019; Qinghua et al., 2022). Its use also ensures comparability with previous Burundian studies that employed the same method (Bashahu & Ndacayisaba, 2024). This model is expressed as (Vernet & Fabregat, 2023):

$$H(\mathrm{MJ/m^2/day}) = H_0\left(a + b\frac{S}{S_0}\right)$$

Where:

- a=0.22 and b=0.54
- S is the mean daily number of sunshine duration (h)
- $H_0$is the extra-terrestrial Radiation
- S_0 is the maximum possible daily sunshine duration (h)

The extraterrestrial radiation is estimated using the following equation (Iradukunda & Chiteka, 2023):

$$H_0(\mathrm{MJ/m^2/day}) = 37.6d_r(\cos\phi\cos\delta\sin\omega_s + \omega_s\sin\phi\sin\delta)$$

where:

- d_r is the eccentricity correction factor of the Earth's orbit.
- ω_s is the sunset hour angle, in radians.
- ϕ is the latitude of the location, in radians.
- δ is the solar declination, in radians.

3.4. Wind speed analysis

The wind data was analyzed to determine the wind speed characteristics based on monthly variation and frequency distribution. The wind power density was also calculated to assess the energy potential of the wind resource in the study area. Analyzing wind power density data helps determine if a location is suitable for wind energy generation.

3.4.1. Monthly wind speed distribution

The wind speed monthly distribution illustrates the occurrence of wind speed within distinct speed ranges. Knowing the monthly wind speeds helps plan renewable energy efficiently, especially for optimizing wind power generation. Wind speed directly affects the energy produced by wind turbines. Hence, it is important to identify periods with consistently high wind speeds. Studying monthly wind patterns helps energy planners predict seasonal variations, ensuring a stable energy supply. These measures ultimately help make wind energy projects more sustainable and profitable. Furthermore, wind speed distribution helps select and design wind turbines for specific wind conditions. Turbines can be optimized for most occurring wind speeds, maximizing energy output and economic viability.

3.4.2. Wind direction frequency distribution

The wind direction is a key factor that cannot be overlooked when assessing wind energy in a given location. Without considering wind direction, any study of wind power in a specific area would be utterly pointless. Wind resources vary based on wind direction, especially in areas with low wind speed and complex terrain.

Furthermore, it is important to note that wind speed and wind direction are linked as interdependent variables. Analyzing these variables helps to understand wind power potential and optimize wind turbine placement for better efficiency (Capozzi et al., 2020; Feng & Wang, 2021; Zhou et al., 2022).

In this study, the lack of recorded wind direction data for the specific period presented a significant challenge. To overcome this challenge, wind rose data from Meteoblue was utilized. The Meteoblue data are derived from 30 years of hourly weather simulations using the ERA5T dataset. Meteoblue's wind rose data helped to analyze wind patterns during the study period, offering insights into wind direction variations throughout the year at study locations (Dayal et al., 2021; Lagili et al., 2023).

3.4.3. Wind Power Density Calculation

Wind Power Density (WPD) is the amount of available power in the wind over a specific area. Wind power density plays a crucial role in the selection of wind energy projects. It allows us to pinpoint locations with ample wind speeds to generate electricity efficiently. The wind power density of a site directly influences the design and capacity of wind turbines.

By analyzing the projected wind power density, it allows to strategically choose and enhance turbines to achieve maximum energy output. Locations with high wind power density offer greater potential for energy production, making wind energy projects a highly lucrative investment (Al-Abbadi, 2005; Himri et al., 2012, 2016). Table 1 classifies WPD into four categories at a height of 12 meters above ground level (Hoxha et al., 2024). This helps to assess the potential of wind energy based on WPD values. The wind power density is computed using the following formula (Bilir et al., 2015; Carta et al., 2008):

$$WPD = \frac{1}{2}\rho v^3 \quad (1)$$

Where:

- WPD is the wind power density (in watts per square meter, W/m^2),
- ρ is the air density (in kilograms per cubic meter, kg/m^3), in this study the standard air density of 1.225 kg/m^3 has been used.
- And v is the wind speed (in m/s).

The wind speed is a crucial factor, as the power density obtainable from the wind is directly related to the cube of the wind speed. This signifies that even small increases in wind speed lead to significant enhancements in wind power density (Zou et al., 2020).

Table 1 Wind power density classes at 12 m.a.g.l (Placide et al., 2021)

WPD Class	WPD (W/m^2)	Suitability
Class 1	WPD< 25	Weak Resource
Class 2	25 <WPD< 75	Weakly Good
Class 3	75 <WPD< 175	Good
Class 4	WPD>175	Very Good

3.5. Justification and workflow

The combination of WPD and Angström–Prescott modeling was selected to enable a comprehensive assessment of wind and solar resources using available datasets. WPD quantifies wind energy potential across seasons, while the Angström–Prescott model provides long-term estimates of solar irradiance from sunshine duration, making both methods suitable for evaluating resource complementarity in hybrid PV–wind system planning.

A schematic workflow (Fig. 2) summarizes the methodology: data collection → preprocessing & homogenization → solar and wind resource assessment → seasonal complementarity analysis → hybrid system design recommendations. This visual guide clarifies the sequence of steps and the rationale for the selected approach.

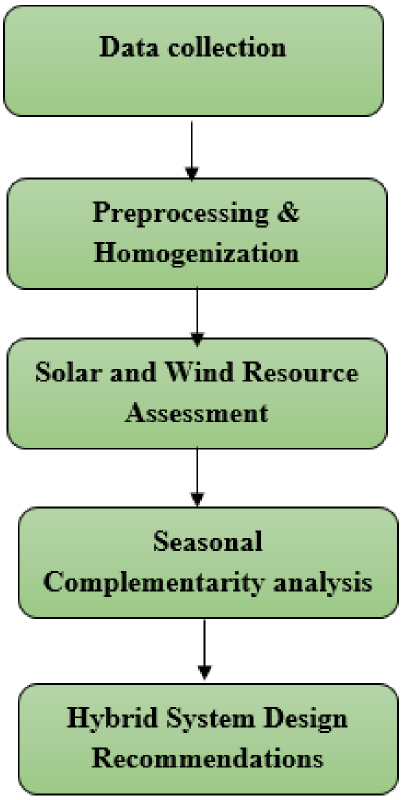

Fig. 2 Methodology

4. RESULTS

4.1. Wind speed variation and power density estimation

Accurate wind data assessment is a crucial step in evaluating the feasibility of wind energy systems, particularly for rural electrification and hybrid renewable energy projects. This section presents a comprehensive analysis of wind resource availability based on key parameters such as wind speed, direction, and frequency distribution over time. Using long-term meteorological data, the objective is to identify patterns and trends that influence the viability of wind energy generation at the selected site. The assessment also involves the calculation of power density to estimate the energy output and inform optimal turbine selection.

4.2. Wind speed

Fig. 3 presents the monthly mean wind speed distribution for the study area.

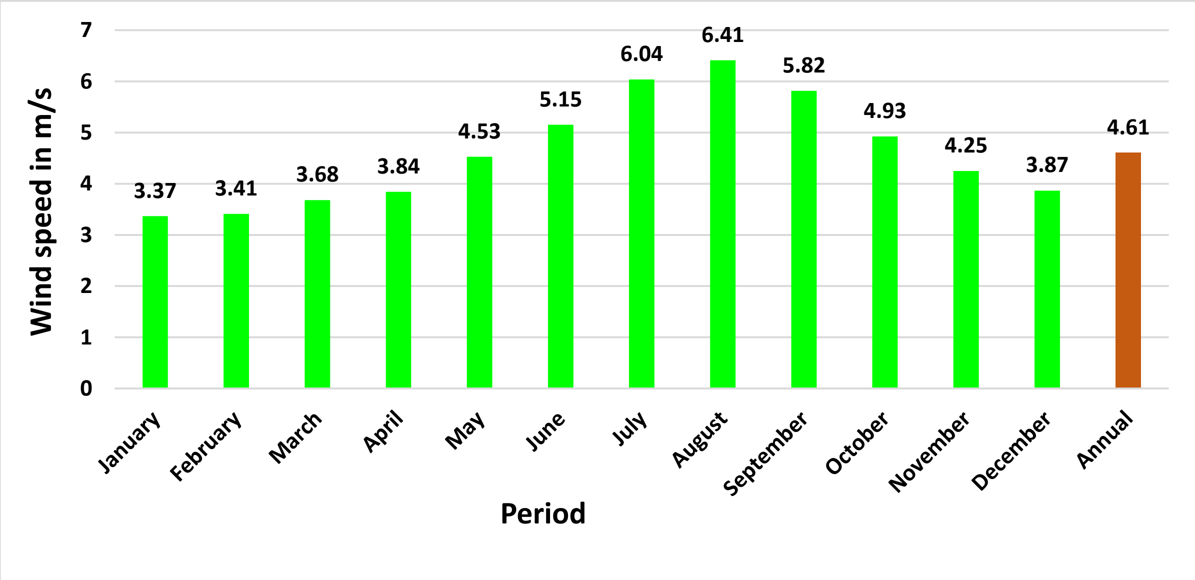

Fig. 3 Average Wind speed monthly variation

The values range from 3.37 m/s in January to 6.41 m/s in August. Wind speeds are relatively low during the first four months of the year, varying between 3.37 and 3.84 m/s. From May onwards, wind speed increases steadily, reaching 5.15 m/s in June, 6.04 m/s in July, and peaking at 6.41 m/s in August. After this maximum, a gradual decline is observed, with values decreasing to 5.82 m/s in September, 4.93 m/s in October, 4.25 m/s in November, and 3.87 m/s in December. The computed annual average wind speed is 4.61 m/s.

The distribution of wind speed frequencies is shown in Fig. 4.

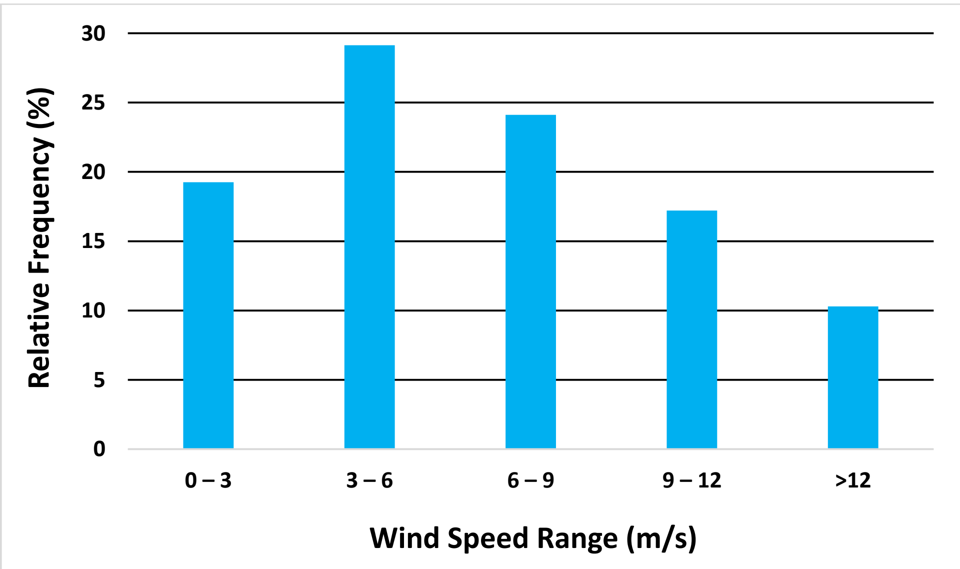

Fig. 4 Wind speed relative frequency

As illustrated in Fig. 4, the wind speed distribution shows that the 3–6 m/s range is the most frequent (29.14%), followed by 6–9 m/s (24.11%) and 0–3 m/s (19.25%). Higher wind speeds are also significant, with 9–12 m/s accounting for 17.21% and speeds above 12 m/s for 10.29%. Overall, wind speeds above 6 m/s occur 51.61% of the time, indicating favorable conditions for wind energy generation. These results suggest strong potential for medium to large-scale wind turbines, especially models optimized for rated performance in the 9–12 m/s range. The distribution supports the site's viability for reliable and efficient wind power production.

4.3. Wind direction

The analysis of wind direction distribution, Fig. 5, in the western region of Burundi reveals a highly anisotropic wind pattern, with a strong dominance from the southern direction (S). According to the data, approximately 47% of the wind occurrences originate from the south, making it the most frequent wind direction by a significant margin. This prevailing southerly wind flow could be attributed to regional topographical influences, including the orientation of the Imbo Plain and the presence of Lake Tanganyika, which may generate lake-induced wind patterns.

The wind direction distribution at the study site is presented in Fig. 5.

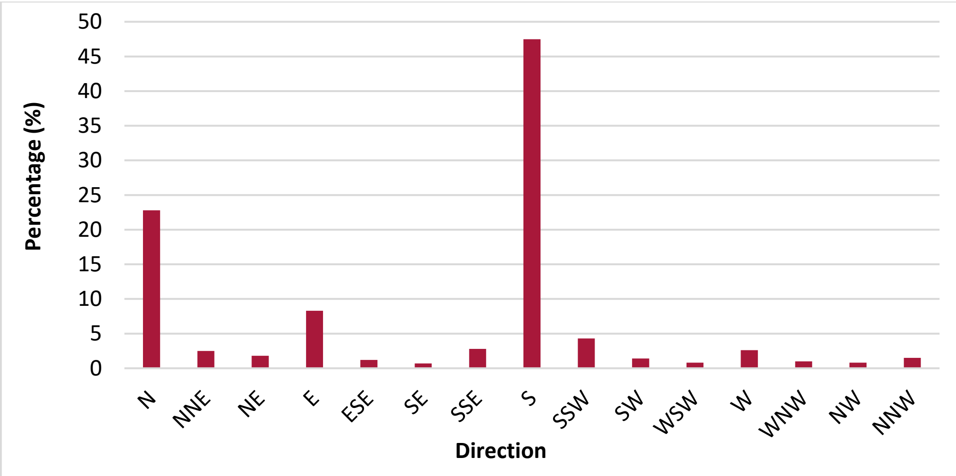

Fig. 5 Wind direction frequency distribution

The northern direction (N) emerges as the second most frequent wind source, contributing about 22% of the total distribution. This bimodal pattern, with significant contributions from both the north and the south, suggests a potential seasonal reversal or alternation of dominant wind directions, possibly linked to the Intertropical Convergence Zone (ITCZ) movements or local thermal gradients.

Other directions, such as east (E) and southeast (SE), show moderate frequencies, generally ranging from 4% to 9%, while wind directions from the west and northwest sectors, including W, WNW, NW, and NNW, are minimally represented, each accounting for less than 3%. This skewed distribution indicates that westerly winds are rare in this region, reinforcing the south-north alignment of wind flows.

This wind directionality has important implications for wind energy development. Wind turbines and small-scale wind systems should be optimally oriented to capture wind from the southern and northern sectors, where the majority of kinetic wind energy is concentrated. Additionally, the clear dominance of the southerly wind suggests that site selection for wind energy installations should prioritize locations with unobstructed southern exposure, such as open plains or elevated zones facing south. This directional consistency could simplify the design and orientation of wind energy systems, enhancing efficiency and output.

4.4. *Wind power density*

Fig. 6 illustrates the monthly and annual variations of wind power density (WPD) at the study site.

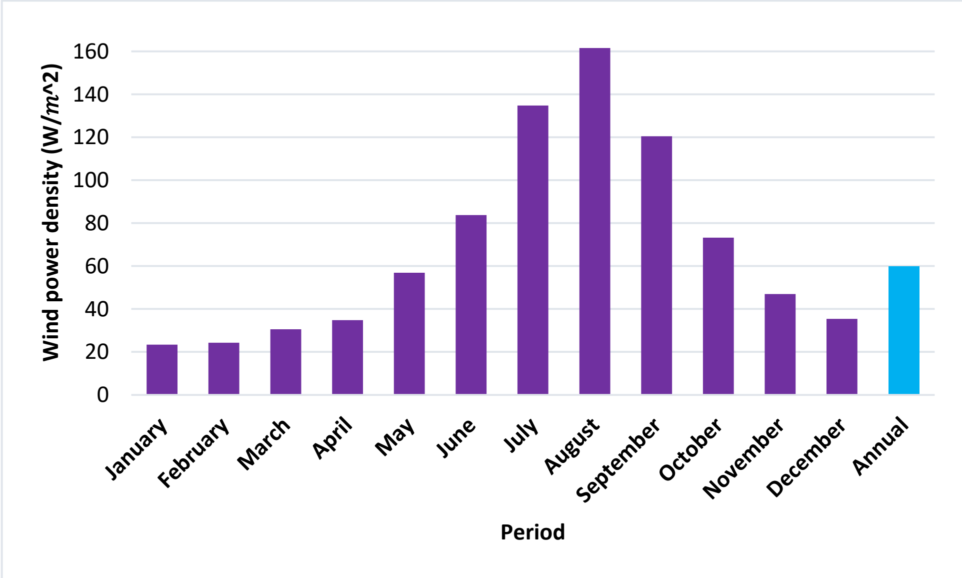

Fig. 6 Monthly and annual wind power density

During the first quarter of the year (January to March), WPD values remain very low, ranging between 20 and 30 W/m^2. According to the classification scale, these values correspond to Class 1–2, which indicates a weak to weakly good resource. This suggests that the contribution of wind energy in this period is marginal and insufficient for significant standalone electricity generation. For clarity, Wind Power Density (WPD) is classified into four standard categories at 12 m above ground level: Class 1 (< 25 W m^{-2}, weak resource), Class 2 (25–75 W m^{-2}, weakly good), Class 3 (75–175 W m^{-2}, good resource), and Class 4 (> 175 W m^{-2}, very good resource).

A gradual improvement is observed from April to May, with WPD values increasing into the range of 30–60 W/m^2, still within Class 2 (weakly good). Although this period shows better potential than the first quarter, wind exploitation remains limited and would require hybridization with other energy sources to ensure reliability.

The situation changes significantly from June to October, which represents the core wind season. June records about 85 W/m^2, which falls into Class 3 (good resource). The resource potential continues to improve in July (≈130 W/m^2) and reaches its peak in August with ≈160 W/m^2, remaining within Class 3 but close to the threshold of Class 4 (very good resource). September and October sustain relatively strong values of 120 W/m^2 and 80 W/m^2, respectively, both within Class 3 (good). This period therefore represents the optimal window for wind power generation, where projects could achieve meaningful electricity output.

Following this seasonal peak, wind potential declines steadily in November and December, with values dropping back to 30–40 W/m^2, placing them in Class 2 (weakly good). This closing period of the year, similar to the first quarter, offers limited opportunity for wind exploitation.

The annual mean wind power density is about 60 W/m^2, which corresponds to Class 2 (weakly good resource). This indicates that, while certain months of the year provide a good and reliable resource (June–October), the overall annual average is only marginal. Consequently, the site cannot be considered suitable for large-scale standalone wind power projects. However, the strong mid-year seasonality suggests that wind energy could play a valuable role as part of a hybrid renewable energy system, particularly in combination with solar PV, which often shows complementary generation patterns.

4.5. Solar data analysis

This section analyzes the available daily sunshine duration records to evaluate the solar resource at the study site. It is organized into two main parts: the first subsection examines the average daily sunshine duration for each month to identify seasonal trends and the consistency of solar availability throughout the year; the second subsection applies the Ångström–Prescott (A–P) empirical model to estimate global solar radiation based on the recorded sunshine hours. This combined approach provides a practical and data-driven foundation for assessing the feasibility, sizing, and expected performance of photovoltaic (PV) systems in the selected region.

4.5.1. Sunshine duration variation

Fig. 7 shows the monthly and annual sunshine duration at the study site, showing a generally favorable solar resource. Sunshine hours range between 5 and 9 hours per day, with the lowest values recorded in February and November (≈5 h/day), while the maximum occurs in July (≈9 h/day).

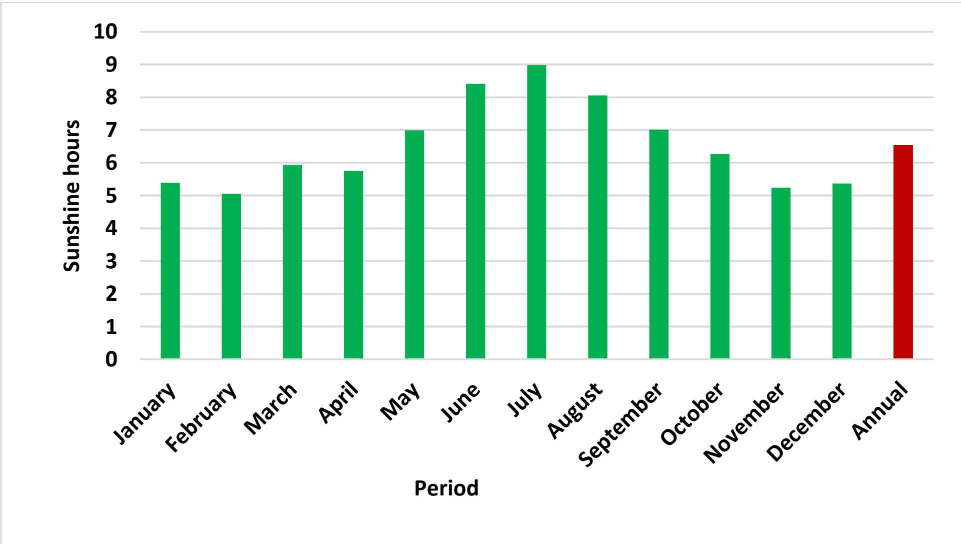

Fig. 7 Monthly and annual sunshine duration

A prolonged period of high sunshine duration is observed between May and September (7–9 h/day), which coincides with the dry season. This period provides optimal conditions for solar energy generation, as reduced cloud cover enhances radiation availability and system reliability.

In contrast, the months from October to April register moderate sunshine levels of 5–6 h/day. Despite higher cloudiness associated with the rainy season, these values remain sufficient to support consistent solar power production. Overall, the annual mean of about 6.5 h/day confirms the strong and reliable solar potential of the site. This stability highlights its suitability for year-round photovoltaic applications, minimizing the risk of seasonal energy deficits.

4.5.2. Seasonal and Annual Solar Irradiance

Fig.8 depicts the estimated monthly global solar irradiance at the study area.

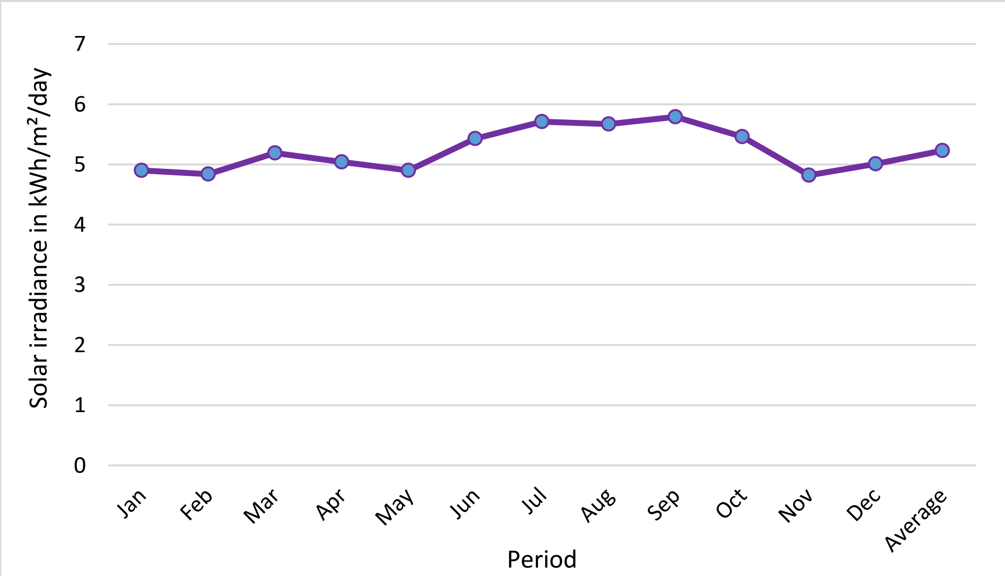

Fig. 8 Estimated monthly global solar irradiation

Findings ascertain that the estimated global solar irradiance in Bujumbura ranges between 4.8 and 5.8 $kWh/m^2/day$, confirming the region's strong potential for photovoltaic applications. The variability between months remains relatively modest, reflecting the tropical climate where solar resources are available throughout the year.

Seasonal variation shows a clear contrast between dry and rainy periods. During the dry season (May–September), irradiance reaches 5.6–5.8 $kWh/m^2/day$, supported by longer sunshine duration and reduced cloud cover. July records the highest sunshine hours, though irradiance remains comparable to June and August due to the lower solar angle limiting extraterrestrial radiation. In contrast, the rainy season (November–February) yields lower values (≈4.8–4.9 $kWh/m^2/day$) as cloudiness and atmospheric moisture reduce solar transmission, though levels remain sufficient for PV generation.

On an annual scale, Bujumbura averages 5.3 $kWh/m^2/day$ (≈1,930 $kWh/m^2/year$), with only ±10% seasonal variation. This stability confirms that PV systems can operate reliably year-round with minimal storage, underscoring solar energy as a robust and sustainable option for electrification in western Burundi.

5. DISCUSSION AND IMPLICATIONS

This study assessed the seasonal behavior of wind and solar resources in western Burundi and analyzed their suitability for renewable energy system design. The results present clear implications for energy planning, hybrid system optimization, and national policy development.

5.1. Wind energy potential

The WPD shows strong variability, with very low values (20–30 W/m^2, Class 1–Class 2) from January to March, making wind unsuitable as a standalone source. Conditions improve modestly in April–May (Class 2), before reaching the main wind season between June and October, when WPD peaks at ~160 W/m^2 (Class 3, near Class 4). This period offers the most favorable opportunity for wind generation. However, the annual mean (≈60 W/m^2, Class 2) confirms that wind resources remain marginal overall, underscoring the need for hybridization with solar PV.

5.2. Solar Energy Potential

Solar resources are consistently strong, with daily sunshine ranging from 5–9 hours and global irradiance between 4.8 and 5.8 kWh/m^2/day (annual mean ≈5.3 kWh/m^2/day). Seasonal variation is modest (±10%), ensuring stable PV generation year-round. Even in the rainy season, 5–6 sunshine hours per day provide adequate output, confirming solar PV as the most reliable renewable option for the site.

5.3. Hybrid System Implications

Wind and solar exhibit complementary seasonal profiles. Wind potential peaks from June to October, partially overlapping with the solar maximum in May–September, while solar output remains strong during low-wind months.

This complementarity underscores the technical viability and cost-effectiveness of solar–wind hybrid systems, which can reduce battery storage needs, increase system reliability, and support continuous supply for rural mini-grids. Hybridization also mitigates the intermittency inherent in relying on either resource alone.

5.4. Regional context

The results align with previous studies in the region. For example, Bashahu & Ndacayisaba (2024) reported average solar irradiance of 5.1–5.4 kWh m^{-2} day^{-1} across several Burundian stations, consistent with the estimated radiation (≈ 5.3 kWh m^{-2} day^{-1}). Similarly, Ayua & Emetere (2024) found comparable irradiance levels (5.0–5.5 kWh m^{-2} day^{-1}) in western Kenya, while wind resource assessments in Burundi (Placide et al., 2021) also reported moderate annual WPD (50–70 W m^{-2}) with seasonal peaks above 120 W m^{-2}, corroborating the seasonal pattern of higher mid-year wind potential.

These agreements suggest that the hybrid configuration recommended in this study is not only technically appropriate for western Burundi but also aligns with broader regional renewable energy characteristics.

5.5. Policy Implications

The integrated wind–solar assessment has several implications for national and local energy policy:

- **Prioritization of Solar PV:** Given the high and stable annual irradiance, solar PV should serve as the principal technology for rural electrification strategies and mini-grid programs.
- **Targeted Deployment of Wind Systems:** Wind energy should be incorporated selectively in areas where mid-year WPD reaches Class 3, thereby enhancing seasonal supply without relying on high-cost standalone wind installations.
- **Hybrid Mini-Grid Expansion:** Policymakers should emphasize hybrid solar–wind systems as a cost-effective strategy to reduce diesel dependence, improve reliability, and decrease storage requirements.
- **Data-Driven Resource Planning:** The demonstrated seasonal complementarity supports the development of long-term energy planning tools, integrating meteorological data into national electrification models.
- **Alignment with SDG7:** Deployment of hybrid renewable systems contributes directly to achieving affordable, reliable, and sustainable energy for all.

6. CONCLUSIONS

This study provides a long-term, integrated assessment of wind and solar resource potential in western Burundi. Solar irradiance averages 5.3 kWh/m^2/day (~1,930 kWh/m^2/year), with minimal seasonal variation, confirming PV as the most dependable renewable option. Although the annual wind resource is modest (~60 W/m^2, Class 2), the pronounced seasonal enhancement between June and October (up to 160 W/m^2, Class 3) enables wind to serve as a valuable supplementary resource.

The quantitative evidence demonstrates that a solar–wind hybrid system can optimize energy reliability and reduce storage needs. PV provides consistent year-round output, while wind enhances production during mid-year peaks. A system design that harnesses the full annual solar resource while integrating seasonal wind contributions can significantly improve off-grid electrification reliability and sustainability in western Burundi.

Above all, this work represents the first comprehensive evaluation of seasonal solar–wind complementarity in the region. The findings offer actionable guidance for hybrid mini-grid planning, strengthen the empirical foundation for renewable energy investment decisions, and support policy initiatives aligned with SDG7.

Limitations and future research directions

This study relied on wind (2013–2020) and sunshine-duration (1977–2017) datasets, which, while reliable, could be complemented by synchronized long-term measurements for finer temporal analysis. Solar irradiance was estimated using the Ångström–Prescott model; future work could integrate satellite or on-site measurements for higher spatial accuracy. The analysis focused on western Burundi, and expanding to other regions would provide a more comprehensive national assessment. Finally, techno-economic evaluation and pilot testing of hybrid PV–wind systems are recommended to optimize system design and operational performance.

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REFERENCE

African Development Bank. (2024). African Economic Outlook 2024. In *African Development Bank*.

https://www.afdb.org/en/documents/african-economic-outlook-2024

Akduğan, U., & Pehlivan, M. (2025). On the causal dynamics between nuclear energy, renewable energy and economic growth in the selected South and Southeast Asia countries: evidence from RALS cointegration and bootstrap asymmetric causality. *Discover Sustainability 2025 6:1*, *6*(1), 958-. https://doi.org/10.1007/S43621-025-01888-1

Al-Abbadi, N. M. (2005). Wind energy resource assessment for five locations in Saudi Arabia. *Renewable Energy*, *30*(10), 1489–1499. https://doi.org/10.1016/j.renene.2004.11.013

Asilevi, P. J., Quansah, E., Amekudzi, L. K., Annor, T., & Klutse, N. A. B. (2019). Modeling the spatial distribution of Global Solar Radiation (GSR) over Ghana using the Ångström-Prescott sunshine duration model. *Scientific African*, *4*.

https://doi.org/10.1016/j.sciaf.2019.e00094

Ayua, T. J., & Emetere, M. E. (2024). *Technical and economic simulation of a hybrid renewable energy power system design for industrial application*.

BARIKUNDA, F., & UFITEYEZU, E. (2025). FEASIBILITY STUDY AND DESIGN OF A SOLAR-WIND HYBRID POWER SYSTEM IN RWANDA. *Journal of Sustainable Engineering & Green Technologies* , *1*(1), 114–122.

https://technology.tresearch.ee/index.php/JSEGT/article/view/24

Bashahu, M., & Ndacayisaba, G. (2024). Estimation of Daily Global Solar Radiation with Different Sunshine-Based Models for Some Burundian Stations. *Energy and Power Engineering*, *16*(01), 1–20. https://doi.org/10.4236/epe.2024.161001

Bashahu, M., Nsabimana, P., Barakamfitiye, J., & Niyukuri, F. (2022). Assessment of the Wind Energy Potential of Two Burundian Sites. *Energy and Power Engineering*, *14*(05), 181–200. https://doi.org/10.4236/epe.2022.145010

Bilir, L., Imir, M., Devrim, Y., & Albostan, A. (2015). Seasonal and yearly wind speed distribution and wind power density analysis based on Weibull distribution function. *International Journal of Hydrogen Energy*.

https://doi.org/10.1016/j.ijhydene.2015.04.140

Capozzi, V., Cotroneo, Y., Castagno, P., De Vivo, C., & Budillon, G. (2020). Rescue and quality control of sub-daily meteorological data collected at Montevergine Observatory (Southern Apennines), 1884-1963. *Earth System Science Data*, *12*(2), 1467–1487. https://doi.org/10.5194/ESSD-12-1467-2020

Carta, J. A., Bueno, C., & Ramírez, P. (2008). Statistical modelling of directional wind speeds using mixtures of von Mises distributions: Case study. *Energy Conversion and Management*, *49*(5), 897–907.

https://doi.org/10.1016/j.enconman.2007.10.017

Dayal, K. K., Bellon, G., Cater, J. E., Kingan, M. J., & Sharma, R. N. (2021). High-resolution mesoscale wind-resource assessment of Fiji using the Weather Research and Forecasting (WRF) model. *Energy*, *232*, 121047. https://doi.org/10.1016/j.energy.2021.121047

Deng, J. M., Wekesa, C. W., Jean, K., Hakizimana, D. D., & Nzabahimana, J. (2025). *Uncovering South Sudan ' s renewable energy potential : a comprehensive evaluation of favourable locations and variability*.

DIVA-GIS. (2025). *Data — DIVA-GIS*. https://diva-gis.org/data.html

Domonkos, P. (2024). Relative Homogenization of Climatic Time Series. *Atmosphere*, *15*(8).

https://doi.org/10.3390/atmos15080957

Ekanem, A. A., & Singh, P. (2024). Design, Economic, and Environmental Analysis of a Stand-Alone Solar Photovoltaic System for a Tailoring Business in Burundi. *2024 IEEE Global Humanitarian Technology Conference, GHTC 2024*, 159–166. https://doi.org/10.1109/GHTC62424.2024.10771541

Eze, V. H. U., Mwenyi, J. S., Ukagwu, K. J., Eze, M. C., Eze, C. E., & Okafor, W. O. (2024). Design analysis of a sustainable techno-economic hybrid renewable energy system: Application of solar and wind in Sigulu Island, Uganda. *Scientific African*, *26*, e02454. https://doi.org/10.1016/J.SCIAF.2024.E02454

Feng, F., & Wang, K. (2021). Merging ground-based sunshine duration observations with satellite cloud and aerosol retrievals to produce high-resolution long-term surface solar radiation over China. *Earth System Science Data*, *13*(3), 907–922. https://doi.org/10.5194/ESSD-13-907-2021

Gurbanov, S. (2024). *Electricity Grids, Smart Grids, and Micro Grids Implications for Electricity Security in Azerbaijan Beyond COP29*.
https://www.researchgate.net/publication/382591660_Electricity_Grids_Smart_Grids_and_Micro_Grids_Implications_for_Electricity_Security_in_Azerbaijan_Beyond_COP29

He, Y., & Wang, K. (2020). Variability in Direct and Diffuse Solar Radiation Across China From 1958 to 2017. *Geophysical Research Letters*, *47*(1). https://doi.org/10.1029/2019GL084570

Heckmann, M., Vassolo, S., & Tiberghien, C. (2016). *Groundwater Vulnerability Map (COP) for the Nyanzari catchment, Gitega, Burundi*.

Himri, Y., Rehman, S., Agus Setiawan, A., & Himri, S. (2012). Wind energy for rural areas of Algeria. *Renewable and Sustainable Energy Reviews*, *16*(5), 2381–2385. https://doi.org/10.1016/j.rser.2012.01.055

Himri, Y., Rehman, S., Himri, S., Mohammadi, K., Sahin, B., & Malik, A. S. (2016). Investigation of wind resources in Timimoun region, Algeria. *Wind Engineering*, *40*(3), 250–260. https://doi.org/10.1177/0309524X16645483

Hoxha, B., Kuriqi, A., & Filkoski, R. V. (2024). Influence of seasonal air density fluctuations on wind speed distribution in complex terrains in the context of energy yield. *Energy, Ecology and Environment*, *9*(2), 175–187.

https://doi.org/10.1007/s40974-023-00301-9

Iradukunda, C., & Chiteka, K. (2023). Angstrom-Prescott Type Models for Predicting Solar Irradiation for Different Locations in Zimbabwe. *Strojniski Vestnik/Journal of Mechanical Engineering*, *69*(1–2), 32–48.

https://doi.org/10.5545/sv-jme.2022.331

IRENA. (2023). *Renewable energy statistics 2023, Abu Dhabi*. www.irena.org

IRENA. (2025). Renewable Power Generation Costs 2024. *International Renewable Energy Agency*. www.irena.org

IRENA and AfDB. (2022). Renewable Energy Market Analysis : Africa and Its Regions, Abu Dhabi and Abidjan. In *Energy Market*.

Jeff Felten, Yara Akkari, S. N. (2023). *Burundi : Small Hydropower and Rural Development*.

Kartal, M. T., Depren, Ö., & Ayhan, F. (2025). Uncovering Displacement between Nuclear and Renewable Electricity Generation for G7 Countries by Novel Wavelet-Based Methods. *International Journal of Sustainable Development and World Ecology*, *32*(2), 186–203. https://doi.org/10.1080/13504509.2024.2423865

Kartal, M. T., Ghosh, S., & Adebayo, T. S. (2023). Renewable energy effect on economy and environment: The case of G7 countries through novel bootstrap rolling window approach. *Renewable Energy*, *216*.

https://doi.org/10.1016/J.RENENE.2023.119057

Kartal, M. T., Mukhtarov, S., & Hajiyeva, N. (2025). Investigation of displacement between main clean energy types: Evidence from leading developed countries through quantile approaches. *Renewable Energy*, *238*.

https://doi.org/10.1016/j.renene.2024.121988

Kartal, M. T., Pata, U. K., Depren, Ö., & Erdogan, S. (2023). Effectiveness of nuclear and renewable electricity generation on CO2 emissions: Daily-based analysis for the major nuclear power generating countries. *Journal of Cleaner Production*, *426*. https://doi.org/10.1016/J.JCLEPRO.2023.139121

Kirikkaleli, D., & Agyemang, E. T. (2025). The dynamics between energy productivity, resource productivity, and environment in France; Empirical findings from Wavelet Quantile methods. *Environment, Development and Sustainability*, 1–23. https://doi.org/10.1007/S10668-025-06383-1/FIGURES/13

Lagili, H. S. A., Kiraz, A., Kassem, Y., & Gökçekuş, H. (2023). Wind and Solar Energy for Sustainable Energy Production for Family Farms in Coastal Agricultural Regions of Libya Using Measured and Multiple Satellite Datasets. *Energies*, *16*(18). https://doi.org/10.3390/en16186725

Lawin, A. E., Niyongendako, M., & Manirakiza, C. (2019). Solar irradiance and temperature variability and projected trends analysis in Burundi. *Climate*, *7*(6), 1–20. https://doi.org/10.3390/CLI7060083

Manirambona, E., Talai, S. M., & Kimutai, S. K. (2022). A review of sustainable planning of Burundian energy sector in East Africa. *Energy Strategy Reviews*, *43*(July), 100927. https://doi.org/10.1016/j.esr.2022.100927

Mellaku, M. T., Wassie, Y. T., Seljom, P., & Adaramola, M. S. (2025). Decentralized renewable energy technology alternatives to bridge manufacturing sector energy supply-demand gap in East Africa: A systematic review of potentials, challenges, and opportunities. *Renewable and Sustainable Energy Reviews*, *216*, 115708. https://doi.org/10.1016/J.RSER.2025.115708

Muyi Yang, B. Y., & Sam Butler-Sloss, E. G. (2025). *China Energy Transition Review 2025 | Ember*.

https://ember-energy.org/latest-insights/china-energy-transition-review-2025/

Niyongabo, J., Zhang, Y., & Ndikumagenge, J. (2023). Analysis of the impact of spatial data quality in the decision-making process: choice of wind turbine site in Burundi. *Applied Mathematical Sciences*, *17*(5), 221–230.

https://doi.org/10.12988/ams.2023.917387

Niyongendako, M., Lawin, A. E., Manirakiza, C., Bazyomo, S. D. Y. B., & Lamboni, B. (2020). Climate Change Impacts on Projected Pv Power Potential Under Rcp 8.5 Scenario in Burundi. *International Journal of Research -GRANTHAALAYAH*, *8*(5), 1–14. https://doi.org/10.29121/granthaalayah.v8.i5.2020.37

Nsabimana, R. (2020). Electricity Sector Organization and Performance in Burundi. *Proceedings*, *58*(1), 26.

https://doi.org/10.3390/wef-06938

Placide, G., & Lollchund, M. R. (2024a). An evaluation of the reliability of the Weather Research Forecasting (WRF) model in predicting wind data: a case study of Burundi. *BMC Environmental Science 2024 1:1*, *1*(1), 1–15.

https://doi.org/10.1186/S44329-024-00001-7

Placide, G., & Lollchund, M. R. (2024b). Wind farm site selection using GIS-based mathematical modeling and fuzzy logic tools: a case study of Burundi. *Frontiers in Energy Research*, *12*, 1353388.

https://doi.org/10.3389/FENRG.2024.1353388/BIBTEX

Placide, G., Lollchund, M. R., & Dalso, G. A. (2021). Wind energy potential assessment of some sites in burundi using statistical modelling. *2021 IEEE PES/IAS PowerAfrica, PowerAfrica 2021*, *1*, 1–5.

https://doi.org/10.1109/PowerAfrica52236.2021.9543186

Qinghua, T., Yujie, L., Xianfang, S., Tao, P., Qinghua, T., Yujie, L., Xianfang, S., & Tao, P. (2022). Spatiotemporal changes of solar radiation and the adaptability comparison of Ångström-Prescott calibration parameters at different temporal scales in China. *Resources Science*, *44*(2), 287–298. https://doi.org/10.18402/RESCI.2022.02.06

REPP. (2025). *Grid-connceted solar PV project | Mubuga, Burundi*. https://repp.energy/project/mubuga-burundi/

Squintu, A. A., van der Schrier, G., Štěpánek, P., Zahradníček, P., & Tank, A. K. (2020). Comparison of homogenization methods for daily temperature series against an observation-based benchmark dataset. *Theoretical and Applied Climatology*, *140*(1–2), 285–301. https://doi.org/10.1007/s00704-019-03018-0

United Nations. (2023). *The-Sustainable-Development-Goals-Report-2023.pdf*.

https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf

United Nations. (2024). *World Population Prospects*. https://population.un.org/wpp/

Vernet, A., & Fabregat, A. (2023). Evaluation of Empirical Daily Solar Radiation Models for the Northeast Coast of the Iberian Peninsula. *Energies*, *16*(6). https://doi.org/10.3390/en16062560

WMO (World Meteorological Organization). (2008). *Guide to Meteorological Instruments and Methods of Observation*. www.wmo.int

World Bank. (2025). *Burundi Overview: Development news, research, data*.

https://www.worldbank.org/en/country/burundi/overview

World Bank Group. (2024). *GDP per capita (constant 2015 US$) - Burundi | Data*.

https://data.worldbank.org/indicator/NY.GDP.PCAP.KD?locations=BI

Xu, Q., Wei, S., Li, Z., & Li, Q. (2025). A New Evaluation of Observed Changes in Diurnal Temperature Range. *Geophysical Research Letters*, *52*(2), e2024GL113406. https://doi.org/10.1029/2024GL113406

Zhou, C., Azorin-Molina, C., Engström, E., Minola, L., Wern, L., Hellström, S., Lönn, J., & Chen, D. (2022). HomogWS-se: a century-long homogenized dataset of near-surface wind speed observations since 1925 rescued in Sweden. *Earth System Science Data*, *14*(5), 2167–2177. https://doi.org/10.5194/ESSD-14-2167-2022

Zou, M., Fang, D., Djokic, S. Z., Di Giorgio, V., Langella, R., & Testa, A. (2020). Evaluation of wind turbine power outputs with and without uncertainties in input wind speed and wind direction data. *IET Renewable Power Generation*, *14*(15), 2801–2809. https://doi.org/10.1049/iet-rpg.2020.0113

Zuhal, M., & Göcen, S. (2024). The relationship between CO2 emissions, renewable energy and economic growth in the US: evidence from symmetric and asymmetric spectral granger causality analysis. *Environment, Development and Sustainability*, 1–22. https://doi.org/10.1007/S10668-024-05002-9/FIGURES/9