

Solar Energy Potential in Burundi: Analysis of Irradiance and Temperature Variations

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Abstract

Burundi faces persistent energy access challenges, with national electrification rates below 12% and continued dependence on hydropower and biomass. Despite abundant solar resources, systematic assessments of irradiance and temperature variability are scarce, limiting evidence-based planning for photovoltaic (PV) deployment. This study evaluates Burundi's solar potential using data from 14 meteorological stations collected between 2011 and 2017. Global horizontal irradiance (GHI) was estimated with the Angstrom-Prescott model, complemented by analyses of sunshine duration and temperature. Results show that southern and western regions, including Makamba, the Imbo Plain, and Gisozi, record the highest average irradiance levels (>5.8 kWh/m²/day), while eastern and northern areas such as Ruyigi and Kirundo remain comparatively lower (<4.6 kWh/m²/day). Seasonal peaks occur during the dry months (June to August), with reductions in the rainy season. Cooler highland zones such as Gisozi (16.6°C average) favor PV efficiency, while warmer lowlands are more suitable for solar thermal applications. This integrated solar resource and temperature mapping provides the first nationwide evidence for optimizing site-specific PV deployment and guiding renewable energy policy in Burundi.

Keywords

Solar Irradiance, Sunshine Duration, Temperature, Angstrom-Prescott, Burundi

1. Introduction

Access to affordable and reliable energy remains one of the most pressing devel-

opment challenges in Sub-Saharan Africa. According to the 2024 Energy Progress Report, the region continues to host 18 of the 20 countries with the largest electricity access deficits. Burundi is consistently ranked among the lowest, with electrification rates below 11% in 2022 and only a slight increase in 2023 (Figure 1). Energy access is particularly uneven, with urban centers better served while rural areas depend almost entirely on traditional biomass, mainly fuelwood and charcoal. This dependence not only accelerates deforestation but also worsens indoor air pollution and greenhouse gas emissions, reinforcing the urgency of diversifying the country's energy mix through renewable alternatives [1]-[4].

The electricity sector in Burundi has historically been dominated by hydropower, accounting for more than 90% of installed capacity [5] [6]. However, effective production is constrained by aging infrastructure, high sedimentation, and climate variability, which reduce output to roughly 30% of potential capacity [4] [7]. In addition, the country faces recurrent droughts, further limiting hydropower availability. Supplementary generation from thermal plants (≈ 41 MW) and the Mubuga solar PV plant (7.5 MW, commissioned in 2021) remain insufficient to keep pace with growing demand. As a result, Burundi experiences chronic electricity shortages, frequent blackouts, and stagnating progress in expanding access [8] [9].

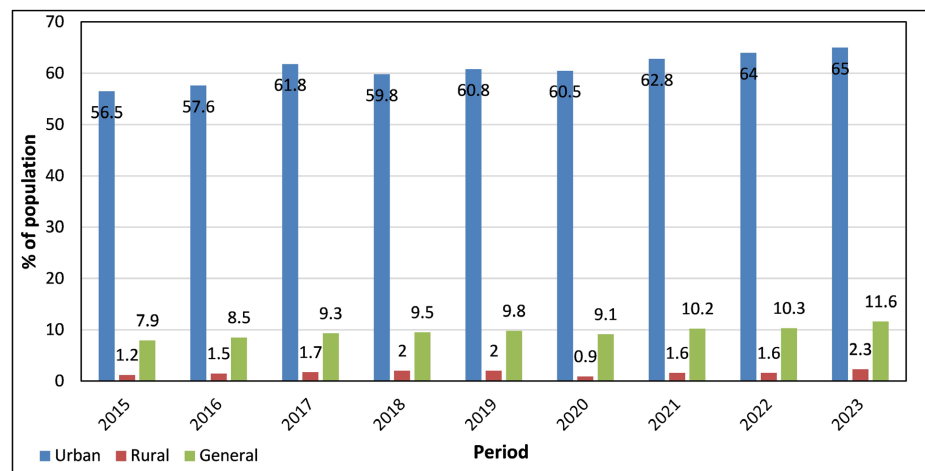


Figure 1. Burundi' population with access to electricity [10].

Demographic dynamics, Figure 2, further complicate this situation. Burundi has one of the highest population growth rates globally, averaging 3.2% per year [11]. This rapid expansion intensifies pressure on an already fragile energy sector, as demand for electricity rises while supply remains constrained.

The widening energy access gap not only slows economic development but also deepens environmental degradation as households turn to unsustainable biomass fuels [12] [13]. Without a fundamental shift toward renewable energy, Burundi risks falling further behind in achieving Sustainable Development Goal 7 (SDG7), which calls for universal access to modern, reliable, and affordable energy services by 2030 [14]-[16].

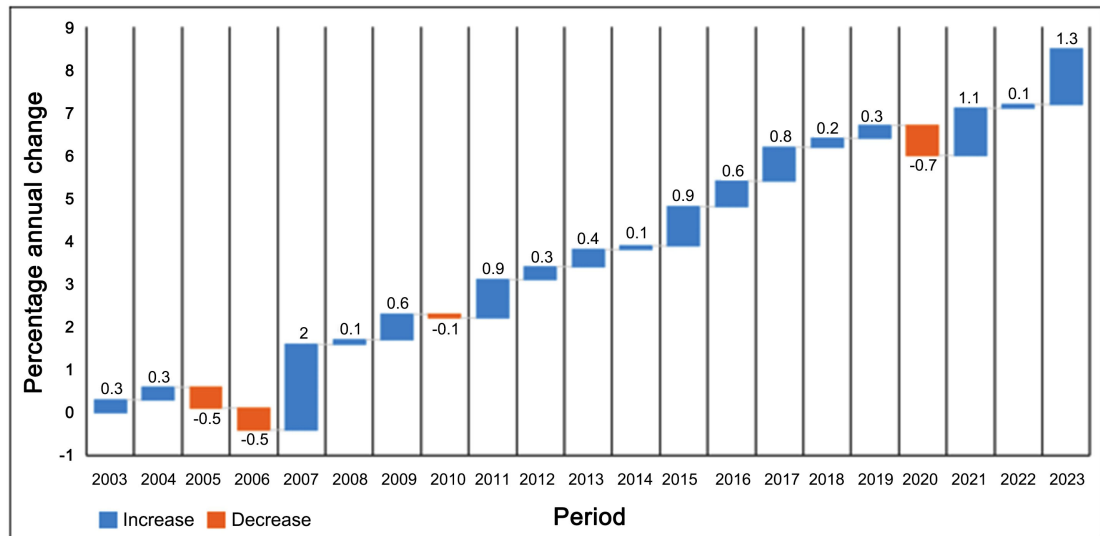


Figure 2. Electricity access annual change.

Solar energy represents a particularly promising solution. Owing to its equatorial location, Burundi receives an estimated average annual solar insolation of about 2000 kWh/m² [17] [18]. Neighboring countries such as Rwanda and Kenya have already scaled up solar deployment, while Burundi has lagged behind despite similar resource availability. Previous studies have acknowledged the potential for solar energy in the country [19], but comprehensive empirical analyses remain scarce. Specifically, no prior work has systematically combined solar irradiance estimation with sunshine duration and temperature mapping across different climatic zones. Such analyses are critical for identifying the most suitable sites for photovoltaic (PV) or solar thermal technologies, optimizing system design, and informing national energy policy.

The importance of considering both irradiance and temperature cannot be overstated. While high irradiance supports greater energy yields, elevated temperatures reduce PV module efficiency. Conversely, cooler highlands may have slightly lower irradiance but offer more favorable thermal conditions for PV systems. Thus, evaluating these parameters jointly provides a more realistic basis for technology selection and deployment.

This study addresses these gaps by assessing Burundi's solar energy potential using seven years of meteorological data (2011-2017) from 14 stations covering lowland, midland, and highland regions. Global horizontal irradiance (GHI) was estimated using the Angstrom-Prescott model, which is well-suited to data-scarce contexts. Sunshine duration and temperature variations were also analyzed to provide a holistic picture of resource availability and system efficiency. The study delivers the first integrated solar resource and temperature mapping for Burundi, offering valuable insights for policymakers, investors, and planners. By identifying priority regions for solar deployment and highlighting the complementary roles of PV and solar thermal applications, the findings contribute directly to ongoing

national efforts toward sustainable electrification and energy diversification.

2. Methodology

2.1. Study Area and Data

This study covers Burundi, a small equatorial country in East Africa characterized by diverse topography ranging from the low-lying Imbo Plain to the highlands of Gisozi and Mpota. Fourteen meteorological stations distributed across different climatic zones were selected to capture this diversity (**Figure 3**). The stations span elevations between 783 m (Bujumbura) and 2160 m (Mpota), thereby representing both warm lowlands and cooler highlands.

Meteorological data for the period 2011-2017 were obtained from the Burundi Geographic Institute (IGEBU). The dataset includes monthly averages of sunshine duration as well as daily minimum and maximum air temperatures. These variables were selected due to their availability and relevance for estimating solar irradiance and assessing photovoltaic (PV) system performance.

To account for topographic influences, a 30 m-resolution Digital Elevation Model (DEM) was processed using ArcMap GIS software, with geographic datasets sourced from DIVA-GIS [20]. Beyond providing spatial context, the DEM was used to analyze correlations between elevation and observed patterns in cloud cover, sunshine duration, and temperature variability, as reported in the Results section. This approach allowed for assessing how topography shapes the spatial distribution of solar resources, highlighting regions where altitude significantly modulates insolation and PV potential.

2.2. Solar Irradiance Estimation

Global horizontal irradiance (GHI) was estimated using the Angstrom-Prescott (A-P) model, which relates sunshine duration to extraterrestrial radiation. This empirical model has been extensively validated in data-scarce regions of Sub-Saharan Africa and provides reliable results where direct pyranometer measurements are lacking [21]-[23]. The general form of the model is [24]:

$$H = H_0 \left(a + b \frac{n}{N} \right)$$

where:

- H = global solar radiation on a horizontal surface (MJ/m²/day),
- H_0 = extraterrestrial radiation on a horizontal surface (MJ/m²/day),
- n = measured sunshine duration (hours),
- N = maximum possible sunshine duration (hours),
- a, b = empirical constants.

For this study, constants $a = 0.25$ and $b = 0.54$ were adopted based on calibration studies conducted in Sub-Saharan Africa [25]-[28]. Extraterrestrial radiation (H_0) was calculated for each station using latitude-specific astronomical equations [29] [30].

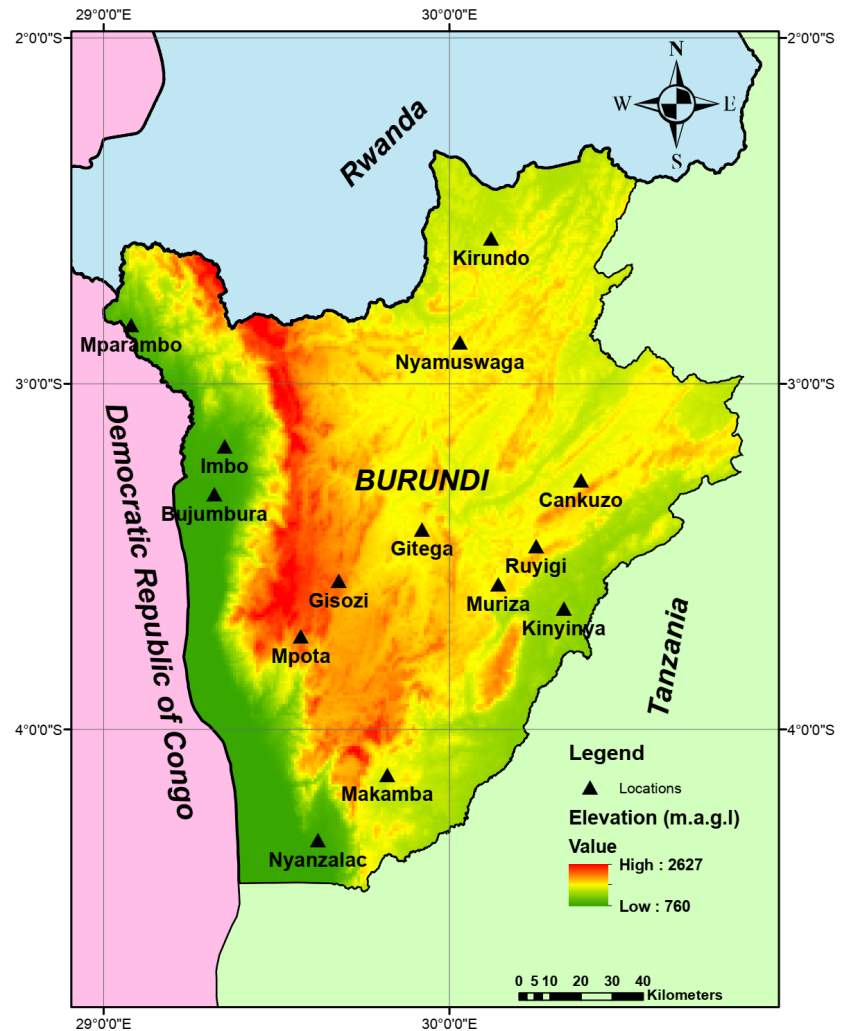


Figure 3. Map of selected meteorological station locations.

2.3. Classification of Solar Radiation

To assess the suitability of different regions for solar energy applications, the estimated irradiance values were classified into categories based on internationally recognized thresholds [31]-[33]. This classification provides a standardized benchmark to evaluate whether a location is more appropriate for photovoltaic (PV) deployment, solar thermal systems, or only small-scale niche applications [34].

Table 1 summarizes the adopted classification scheme. Regions with very high irradiance levels (>6.9 kWh/m²/day) are considered optimal for both large-scale PV and thermal solar power (TSP). Areas with high irradiance (5.6 - 6.9 kWh/m²/day) remain suitable for a wide range of solar technologies. Moderate irradiance values (4.2 - 5.6 kWh/m²/day) can still support PV and solar water heating but may limit system efficiency. Locations with low irradiance (2.8 - 4.2 kWh/m²/day) are generally restricted to small-scale applications, while very low irradiance (<2.8 kWh/m²/day) is insufficient for conventional solar systems, leaving only specialized uses such as calculators or small devices.

2.4. Analytical Approach

The analysis followed four main steps:

- 1) Data compilation and quality control—sunshine duration and temperature data were checked for consistency and completeness.
- 2) Estimation of GHI—the A-P model was applied to derive solar irradiance for each station.
- 3) Classification and mapping—irradiance values were categorized according to the thresholds in **Table 1** and visualized using GIS.
- 4) Spatio-temporal analysis—seasonal, monthly, and spatial variations of irradiance and temperature were analyzed to identify patterns relevant for PV and solar thermal applications.

This integrated approach allows for both quantitative estimation of solar resources and qualitative assessment of their suitability for different energy applications across Burundi.

Table 1. Classification of solar radiation levels and suitability for applications.

Classification	Solar Radiation kWh/m ² /day	Description
Very High	>6.9	Optimal for large-scale PV and solar thermal power (TSP).
High	5.6 - 6.9	Suitable for various solar technologies, including PV and solar thermal systems.
Moderate	4.2 - 5.6	Adequate for most solar applications, including PV and solar water heating.
Low	2.8 - 4.2	It may limit the efficiency of solar power systems, suitable for small-scale solar applications.
Very Low	<2.8	Limited solar energy potential; suitable for niche applications like solar-powered calculators.

3. Results

3.1. Sunshine Duration

Sunshine duration (**Figure 4**) varies considerably across Burundi, reflecting the influence of topography and seasonal weather patterns. Among the 14 stations analyzed, Cankuzo recorded the highest average value of 8.2 hours per day, followed by Kinyinya (7.6 h/day) and the Imbo Plain (7.58 h/day). In contrast, the eastern stations of Muriza and Ruyigi experienced the lowest averages, at 5.18 h/day and 5.21 h/day, respectively.

Seasonal variation is pronounced. Sunshine duration peaks during the dry months of June to August, when cloud cover is minimal, and declines sharply during April and November, which coincide with the main rainy seasons. These patterns directly influence solar resource availability, as longer sunshine duration corresponds to greater potential irradiance.

The spatial distribution indicates that lowland and western regions, such as the

Imbo Plain, enjoy longer sunshine hours compared with highland and eastern stations, where cloud formation and rainfall are more persistent. These findings are consistent with regional studies that highlight the role of altitude and rainfall regimes in shaping solar exposure in East Africa [35]-[37].

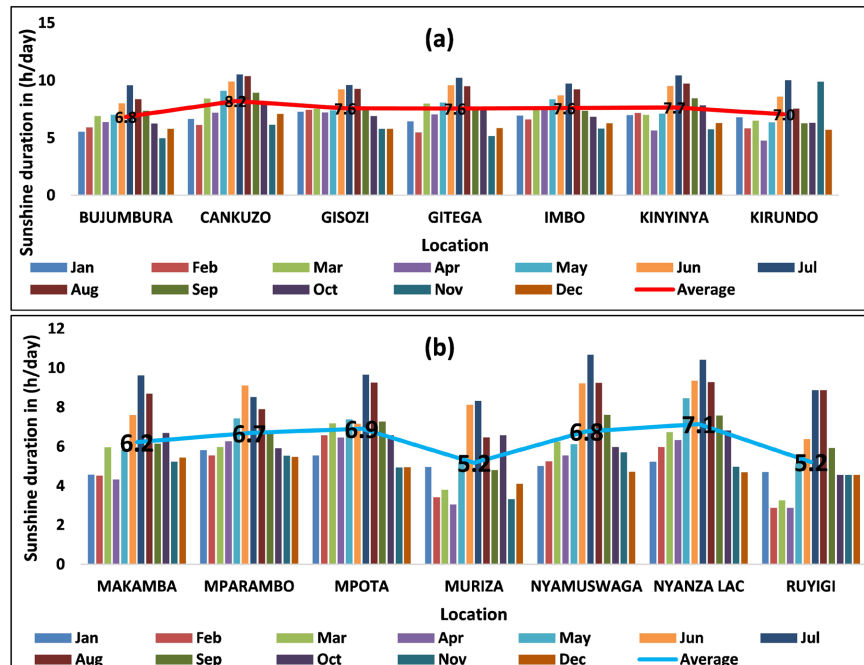


Figure 4. (a) & (b) Monthly variation of sunshine duration across selected stations.

3.2. Temperature Variation

Temperature patterns across Burundi, depicted in **Figure 5** and **Figure 6**, exhibit both spatial and seasonal variability, strongly influenced by altitude. Maximum daily temperatures are consistently higher in lowland regions such as Bujumbura, the Imbo Plain, and Mparambo, where values peak during August and September. In these areas, average maximum temperatures frequently exceed 28°C , creating warmer conditions that can reduce photovoltaic (PV) module efficiency.

In contrast, high-altitude stations such as Gisozi and Mpotia experience considerably cooler conditions. Maximum daily temperatures in these regions average below 23°C , while minimum temperatures often fall below 15°C during the year. This thermal advantage enhances PV efficiency by reducing module overheating, even when irradiance values are slightly lower.

The pronounced temperature gradient between lowlands and highlands underscores the importance of matching technology choices with local climatic conditions. Lowland areas, though characterized by higher irradiance, are better suited for solar thermal applications such as water heating or industrial steam generation, which benefit from elevated ambient temperatures. Conversely, cooler highland regions provide an optimal environment for PV deployment, ensuring higher conversion efficiency and stable system performance.

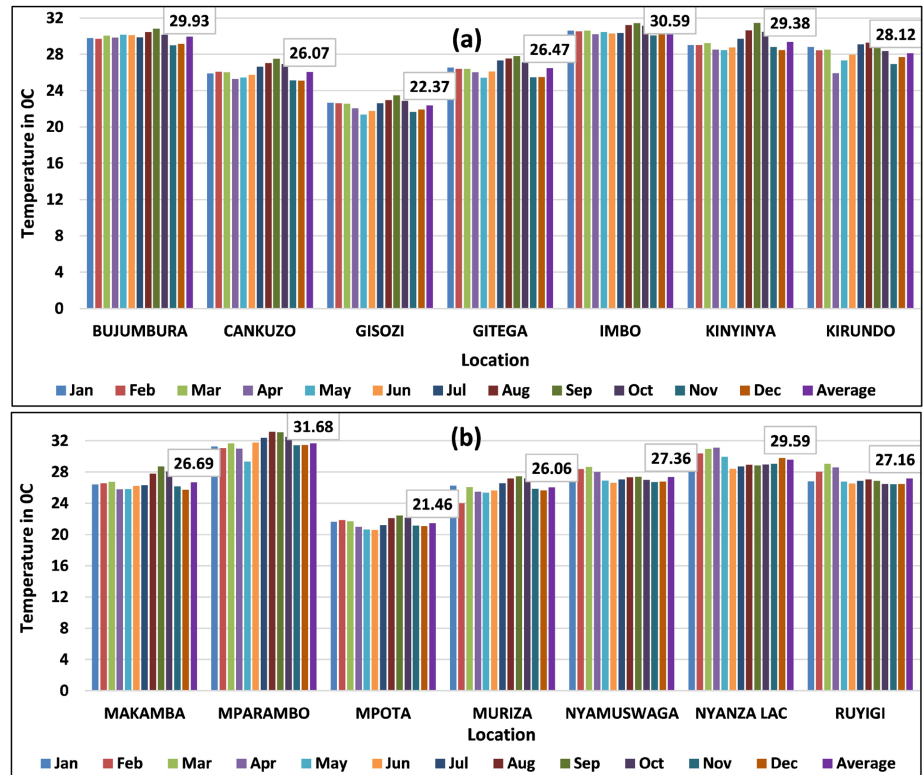


Figure 5. (a) & (b) Monthly maximum temperature variations across stations.

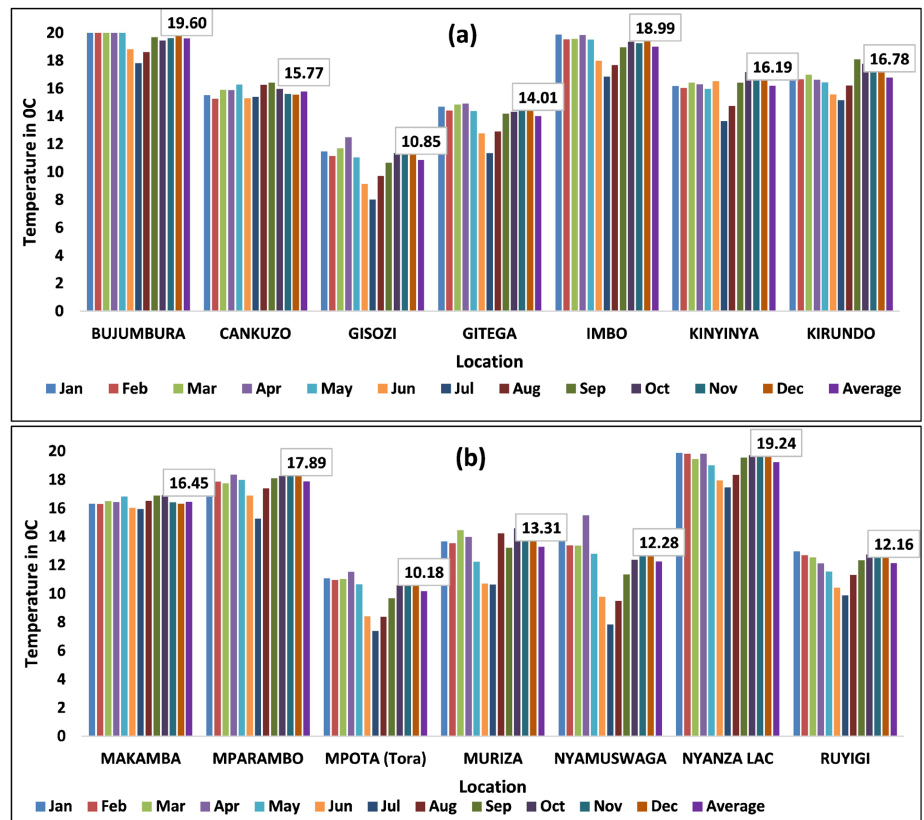


Figure 6. (a) & (b) Monthly minimum temperature variations across stations.

These spatial temperature dynamics highlight the need to integrate thermal considerations into solar planning, rather than focusing solely on irradiance.

3.3. Solar Irradiance Levels

Estimates of global horizontal irradiance (GHI) reveal substantial variation across both space and seasons in Burundi. Annual averages across the 14 meteorological stations range from 4.6 to 5.9 kWh/m²/day (Figure 7), confirming the country's strong baseline potential for solar energy.

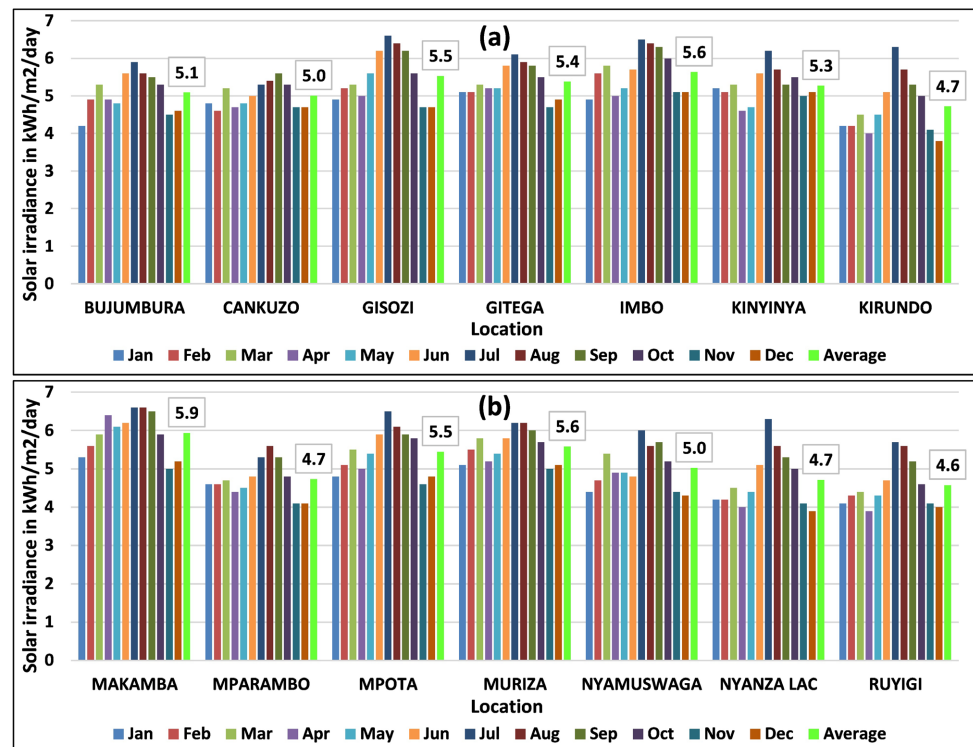


Figure 7. (a) & (b) Monthly trends of solar irradiance.

The highest average irradiance was recorded in Makamba (5.9 kWh/m²/day), followed closely by the Imbo Plain and Muriza (\approx 5.6 kWh/m²/day). In contrast, the eastern and northern stations, particularly Ruyigi (4.6 kWh/m²/day) and Kirundo/Nyanza Lac (\approx 4.7 kWh/m²/day), exhibited the lowest averages. This distribution suggests a clear gradient, with southern and western regions receiving consistently higher irradiance compared with northern and eastern locations.

Seasonal variability is equally pronounced. Irradiance levels decline during the rainy months of March-May and October-November due to increased cloud cover, whereas the dry season (June to August) exhibits peak irradiance values exceeding 6.0 kWh/m²/day at several stations, including Gisozi, Imbo, Mpota, Muriza, and Makamba.

Spatial mapping (Figure 8) confirms these trends, highlighting Makamba and the Imbo Plain as the most resource-rich zones, while Ruyigi, Kirundo, and Nyanza

Lac fall into lower but still viable ranges. Importantly, all stations surpassed the widely recognized threshold of 4.5 kWh/m²/day, reaffirming the technical feasibility of photovoltaic deployment across the entire country.

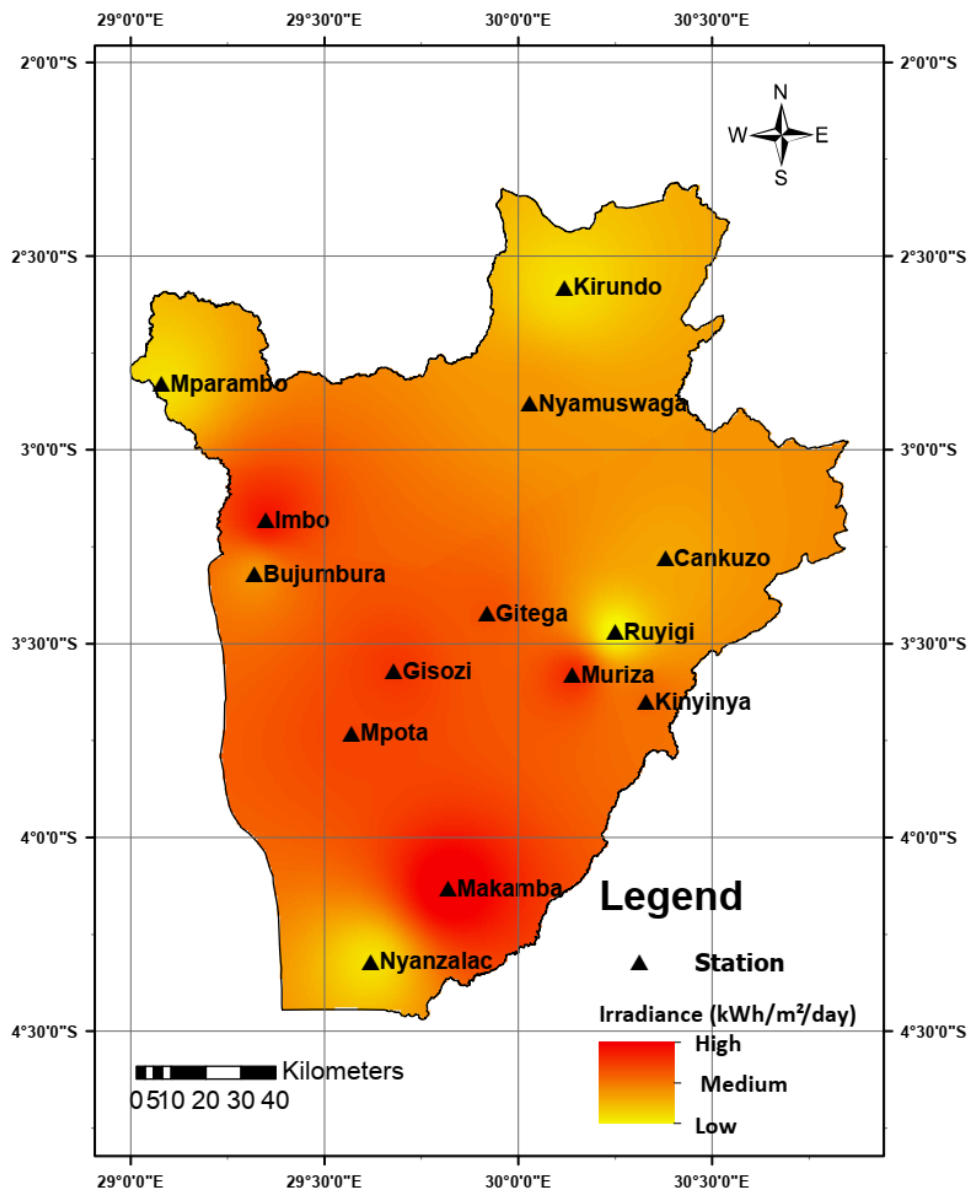


Figure 8. Spatial distribution map of average solar irradiance across Burundi.

The combination of favorable irradiance levels with distinct regional contrasts underscores the importance of spatially differentiated planning for solar energy projects in Burundi.

3.4. Suitability of Solar Irradiance in Burundi

The classification of average daily solar irradiance values highlights three distinct suitability zones for solar energy applications across Burundi (Table 2).

Table 2. Spatial suitability classification.

Suitability Class	Locations	Irradiance (kWh/m ² /day)	Key Advantages	Most Suitable Applications
High	Makamba, Imbo Plain, Muriza	5.6 - 5.9	Long sunshine duration, strong irradiance	Utility-scale PV, hybrid PV-thermal, large mini-grids
Moderate	Gisozi, Mpoti, Kinyinya, Gitega, Bujumbura, Cankuzo, Mparambo	5.0 - 5.5	Cooler conditions enhance PV efficiency	Distributed PV, medium mini-grids, institutional systems
Lower but Viable	Ruyigi, Kirundo, Nyanza Lac	4.6 - 4.9	Adequate but lower irradiance	Small-scale PV, rural off-grid electrification

High-suitability regions include Makamba, the Imbo Plain, and Muriza, with average irradiance values between 5.6 and 5.9 kWh/m²/day. These areas combine long sunshine duration with strong solar intensity, making them optimal for utility-scale photovoltaic (PV) projects, hybrid PV-thermal systems, and large mini-grids. Their favorable conditions position them as priority zones for large-scale solar investment.

Moderate-suitability regions such as Gisozi, Mpoti, Kinyinya, Bujumbura, Gitega, Cankuzo, and Mparambo record averages of 5.0 - 5.5 kWh/m²/day. Although slightly lower in irradiance, their cooler highland conditions enhance PV efficiency, ensuring reliable performance. These areas are particularly suited for distributed PV systems, institutional installations, and medium-sized mini-grids, which can support rural electrification and community services.

Lower but still viable regions include Ruyigi, Kirundo, and Nyanza Lac, with averages ranging from 4.6 to 4.9 kWh/m²/day. While their solar resource is comparatively weaker, these regions still exceed the 4.5 kWh/m²/day viability threshold for PV deployment. Small-scale off-grid systems and household-level solar installations are most appropriate here, providing critical energy access to underserved rural populations.

The classification demonstrates that every region in Burundi possesses technically viable solar potential, though applications differ by location. This differentiation is crucial for guiding investment decisions: high-resource areas should be prioritized for grid-connected or utility-scale projects, while moderate and lower-resource regions are best targeted with decentralized and hybrid solutions.

4. Discussion

Burundi exhibits substantial solar energy potential, with annual irradiance ranging from ≈ 4.6 kWh/m²/day in lower-resource areas (Ruyigi, Kirundo, Nyanza-Lac) to 5.6-5.9 kWh/m²/day in high-irradiance zones (Makamba, Imbo Plain, Muriza). Seasonal variability is pronounced, with dry-season peaks exceeding 6.0 kWh/m²/day and rainy-season lows around 4.5 - 4.7 kWh/m²/day, indicating that most regions meet the >4.5 kWh/m²/day threshold for economically viable PV deployment. Temperature further affects performance, as lowland areas like Bujumbura experience slight efficiency losses, while cooler highlands such as Gisozi maintain higher

PV conversion efficiency. Despite these variations, high-irradiance regions offset thermal losses, ensuring strong year-round energy output.

The 7.5 MW Mubuga PV plant in Gitega illustrates that even moderate-irradiance sites can support utility-scale generation. Findings from high-irradiance areas, including the Imbo Plain (~5.6 - 5.9 kWh/m²/day), confirm the success of existing projects and highlight the potential for future large-scale PV deployment. Southern and western high-irradiance zones are particularly suitable for grid-connected systems, while moderate-resource regions can accommodate decentralized installations to improve rural electrification and reduce reliance on biomass or diesel.

Aligning the >4.5 kWh/m²/day threshold with national renewable energy targets and investment incentives can guide strategic deployment, ensuring that solar energy contributes effectively to Burundi's energy security and sustainable development goals.

5. Conclusions

This study provides the first comprehensive solar irradiance and temperature mapping for Burundi, based on seven years of data from 14 meteorological stations. The analysis shows that several regions, particularly Makamba, Imbo Plain, and Muriza, exhibit high irradiance levels exceeding 5.8 kWh/m²/day, making them highly suitable for PV deployment. Temperature patterns further highlight the advantages of highland regions for PV efficiency and lowland areas for thermal applications.

By providing reliable empirical data and identifying optimal locations, this study helps reduce uncertainty for investors and policymakers in Burundi's solar sector. The spatial mapping and data-driven insights provide actionable guidance for policymakers, investors, and planners, supporting strategic allocation of resources and prioritization of high-irradiance, cooler regions for PV development, while considering hybrid solutions in marginal areas.

Future research should extend these findings by long-term climate projections, land-use constraints, and grid integration considerations, alongside a techno-economic evaluation of the levelized cost of energy (LCOE) for PV systems in both high- and moderate-suitability zones. Such analyses would provide a rigorous, comprehensive assessment of both the technical and economic viability of large-scale and decentralized solar deployment, directly informing strategic investment decisions and sustainable energy planning in Burundi.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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