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Influence of Atmospheric Moisture on Renewable Energy Generation in the Ecological Zones of Ghana

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ABSTRACT

Climate change has intensified global interest in how atmospheric dynamics influence renewable energy systems. Ghana, aiming to expand renewable energy and achieve Sustainable Development Goal 7, faces rising atmospheric moisture across its ecological zones. This study examines how long-term humidity trends affect solar and wind power energy generation using meteorological and satellite data combined with correlation, regression, and spatial analysis to quantify the effects of relative humidity, cloud cover, dew point, temperature, wind speed, and precipitation from 1995 to 2024. Findings show that solar irradiance and photovoltaic performance are reduced by cloudiness and humidity in the Coastal Savannah, while the drier Guinea Savannah records higher irradiance and solar potential. The results confirm an inverse relationship between atmospheric moisture and solar power generation. The study underscores the importance of incorporating climatic factors into national energy planning and technological adaptation to optimise renewable energy systems across Ghana.

KEYWORDS

Climate Change; Atmospheric Moisture; Renewable Energy Generation; Solar Photovoltaic (PV); Wind Energy; Correlation Analysis; Regression Analysis; Ecological Zones.

INTRODUCTION

Energy is pivotal for human development. Every day, societies and people consume energy in order to get access to basic needs such as lighting, cooking, communications, and health care while facilitating bigger development objectives. Meanwhile, while international energy demand continues to increase, the natural systems that supply it are finite. Here, the global world is increasingly getting integrated, and access to clean, low-cost energy has also come to the fore as not just a technological issue but also as the foundation for human well-being, public health, and sustainable social and economic development [1]. However, while global discourse on energy security and sustainability is growing, limited attention has been given to the nuanced role of atmospheric dynamics, particularly humidity, in shaping renewable energy outcomes.

This study does not address how to secure an equitable supply of energy; instead, it focuses specifically on how atmospheric parameters, particularly humidity, cloud cover, and

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temperature, affect the efficiency and performance of solar photovoltaic (PV) systems [2]. Energy poverty still stifles development. 1.4 billion individuals lack electricity, and the vast majority of them, that is, 85 %, live in rural areas. If population growth is not controlled, this number will rise to 2.8 billion in the year 2030, especially if populations continue to rely on inefficient biomass energy sources [3]. Physical limits to infrastructure, restricted finance, and annual variation in water resources continue to undermine energy system reliability in most regions. In West Africa, for instance, historical droughts had caused the closure of major hydropower facilities such as Ghana's Akosombo Dam in 1998 and Nigeria's Kainji Dam in 2001, which drew attention to the susceptibility of conventional energy supply systems to environmental impacts [4,5]. To address these issues, the global community adopted the United Nations Sustainable Development Goals (SDGs) of 2015. Among them is SDG 7, which assures universal access to modern, clean, reliable, affordable energy. To achieve this, infrastructure is not sufficient; but also required are comprehensive climate and energy information, effective monitoring systems, and a sound scientific understanding to guide the shift towards renewable energy [6].

Ghana has embraced this vision. Situated in the tropical belt of West Africa, Ghana's national development plan aligns with the SDGs based on support for the expansion of renewable energy. It consists of three broad ecological zones, coastal, forest, and savannah, each subject to seasonal fluctuations in cloudiness, temperature, and humidity. These are climatic conditions, with the north–south movement of the Inter-Tropical Convergence Zone (ITCZ) (see the Appendix for a full list of symbols) and monsoon activity prevailing to a great extent [7,8] and which has a significant impact on renewable energy technologies' performance, especially solar photovoltaic (PV) systems (see the Appendix for the full list of symbols. This underscores the importance of contextual studies that not only assess solar potential in general but also interrogate how specific atmospheric variables constrain or enhance renewable energy generation across ecological belts.

Solar power has emerged as one of the most practical renewable energy sources in the West African sub-region. Ghana has a mean solar radiation intensity of 5–6 kWh/m^2/day, and hence, high-scale solar investment is made viable [9]. Projects such as the Winneba BXC Solar Plant and the Kaleo and Lawra installations in the Upper West Region show the country's bid for greater solar access. These technologies, while expanding access to clean electricity, remain sensitive to atmospheric parameters such as relative humidity, cloud cover, and temperature, which previous studies have shown to significantly reduce PV efficiency [10,11]. For instance, Mohamed et al. [12] used numerical simulations to conclude that moisture intrusion alters PV electrical performance. Kabré et al. [13] found that PV generation could be reduced by a maximum of 30 % due to humidity in tropical climates. Njok and Ogbulezie [14] also underlined the role of riverine humidity in panel efficiency. Yet, these studies have mostly been short-term, simulation-based, or localised, leaving a critical gap in understanding how long-term atmospheric humidity trends affect renewable energy output at a national scale in Ghana.

However, a key challenge remains: the lack of long-term, spatially explicit studies linking humidity variability with solar PV performance, particularly in Sub-Saharan Africa. Unlike Asia and the Middle East, where dust storms and extreme heat dominate PV efficiency concerns, Ghana faces persistent high humidity in its Coastal Savannah (often exceeding 85 %), which significantly suppresses solar irradiance compared to the relatively drier Guinea Savannah. This ecological contrast makes Ghana a unique case for studying humidity–solar energy interactions at a national scale.

Atmospheric humidity influences include solar technology, thermal environments, and air density, which influence wind power technology. Adkins and Sescu [15] demonstrated that the variation of humidity influences wind turbine performance in agricultural areas, and Avila et al. [16] highlighted climate-resilient infrastructure design for renewable energy for Ghana and the neighbouring nations. Nonetheless, the novelty of this study lies in combining three decades of empirical data with correlation, regression, and spatial analysis to generate an integrated picture of how atmospheric humidity influences both solar and wind systems across Ghana's major ecological zones. Despite these findings, there remains limited empirical data to link variability in long-term atmospheric moisture with renewable energy generation in Ghana's three ecological zones. This limitation exacerbates energy planning, particularly in site suitability assessment, system reliability, and performance optimisation.

Accordingly, this study explicitly addresses the identified research gap by examining the long-term link between atmospheric humidity and renewable power generation in Ghana from 1995 to 2024, thereby offering evidence-based insights absent in earlier works. It is interested in long-term patterns of atmospheric moisture along the coastal, forest, and savannah regions and how they influence the reliability and efficacy of solar PV and wind farms. The study further creates spatial maps and statistical overviews to quantify the effect of atmospheric humidity, hence guiding energy developers, planners, and policymakers committed to creating a climate-resilient and sustainable energy future in Ghana.

METHODOLOGY

Study Area

The study area (**Figure 1**), Ghana, is on the coastal border of tropical West Africa, bounded in latitude 4°44′N and 11°11′N, and longitudes 1°11′E and 3°15′W. The country covers a total land area of approximately 238,535 km^2 and is bounded by Burkina Faso to the north, Côte d'Ivoire to the west, Togo to the east, and the Gulf of Guinea to the South and is characterised by a tropical monsoon climate system. The country is divided into three main ecological zones based on climate, vegetation, and rainfall characteristics: the coastal, forest, and savannah zones. Each of these zones displays distinct climatic patterns that impact atmospheric moisture variability and renewable energy potential. The coastal zones are located along the southern fringe of the country, characterised by relatively high humidity, low rainfall compared to the forest zones, and high solar radiation levels. Cities like Cape Coast, Accra, and Takoradi are located in this zone.

The forest zone is located in the middle belt of the country, experiences the highest rainfall and relative humidity levels, with a dense vegetation cover. Ashanti, Western, and part of the eastern region are the major regions found in this area. The savannah zone, covering the northern part of Ghana, experiences a semi-arid climate with low rainfall and humidity but higher wind speeds. It includes Upper West, Upper East, North East, Northern, and Savannah regions. These ecological zones are ideal for determining how atmospheric moisture components like cloud cover, relative humidity, and water vapour impact the performance of photovoltaic and wind energy systems. The differences in climatic conditions across zones make Ghana a suitable case study for assessing relationships between atmospheric moisture and renewable energy generation potential.

Data acquisition

The study period extends from January 1995 to December 2024, utilizing high-resolution gridded monthly climate data acquired from the NASA Prediction of Worldwide Energy Resources (POWER) platform [17]. The study integrates both spatial and temporal dimensions, employing descriptive statistics, regression analysis, correlation analysis, and geospatial mapping to understand climate-solar interactions across Ghana. Essential methodological factors that either directly or indirectly affect solar irradiance and photovoltaic efficiency were the concentration of the data collection process.

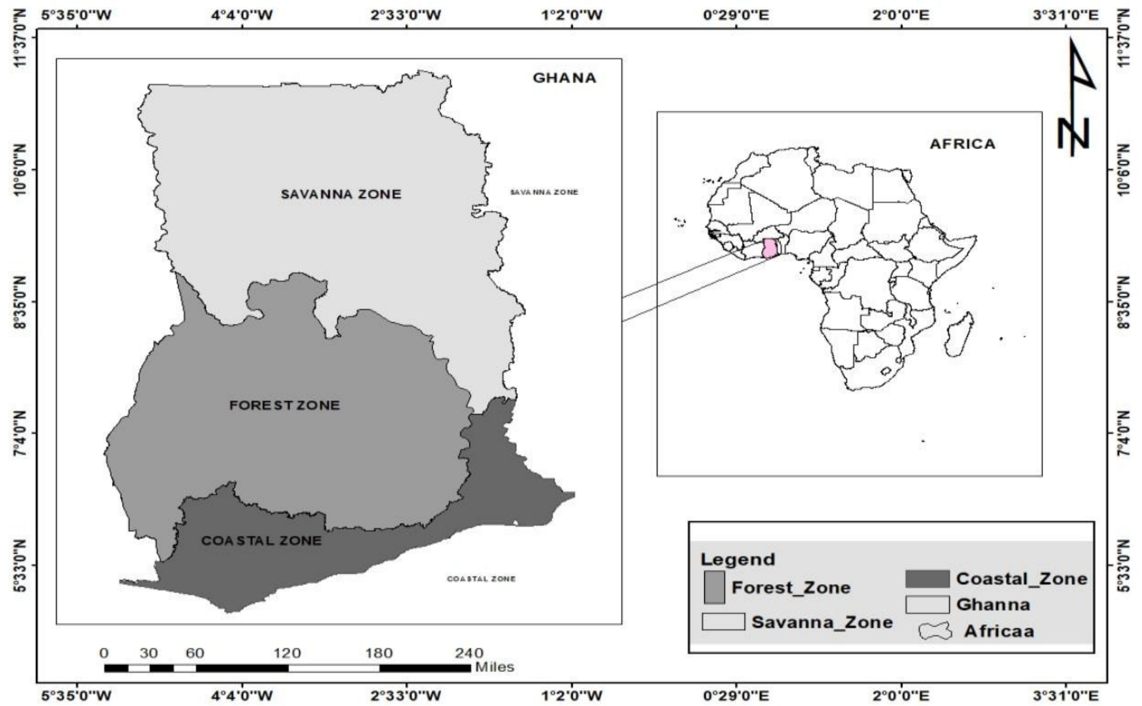

Figure 1. Study area map of Ghana showing the three ecological zones

Dew point, Temperature, Maximum and Minimum Air Temperature, Rainfall, Global Horizontal Irradiance (GHI), Relative Humidity (RH), and Maximum and Minimum Wind Speed are some of these variables (see the Appendix for the full list of symbols). These variables were selected based on well-documented physical relationships with solar irradiance and photovoltaic conversion efficiency. For instance, humidity and dew point reduce irradiance through scattering and absorption, while wind speed and temperature affect convective cooling and air density. Wind speed and temperature variables were incorporated to assess their compounding effects on solar radiation. Moreover, spatial raster data from NASA POWER on photovoltaic output (PVOUT in kWh/kWp) (see the Appendix for the full list of symbols) were obtained from the World Bank Group [18], providing a spatial scenario of the solar potential across ecological zones.

In order to ensure correct spatial alignment, all datasets were collected at a monthly resolution and geographically referenced using latitude and longitude coordinates. The raw datasets were subjected to a detailed pre-processing stage using Google Earth Engine (GEE) and Python programming tools for data wrangling, and Excel and SPSS for visualisation. Monthly labels were standardised and formatted as date and time objects. Since the datasets came from different spatial grids, spatial standardisation was carried out by rounding all latitude and longitude coordinates to one decimal place. This approach, while improving integration across grids, introduces potential spatial uncertainty since rounding can smooth fine-scale variability; however, it ensures comparability and reduces misalignment errors when overlaying datasets. The resulting dataset was structured to include time, latitude, longitude, and the associated values for each variable. Classification of ecological zones was carried out based on geographic latitude.

All locations with a latitude less than or equal to 6.0°N were categorised as belonging to the coastal zone. Areas between 6.1° and 8.5° were classified under the forest zone, while all locations above 8.5°N were considered part of the savannah zone. These classifications allowed for detailed zonal analysis of climate and solar potential dynamics. To improve transparency and reduce noise, monthly averages were computed for temperature and wind speed by averaging their respective maximum and minimum values: $T\_avg = (T\_max + T\_min) /$

$2, W\_avg = (W\_max + W\_min) / 2$. The final dataset was refined to include only complete observations, omitting any records with missing values. Over 32,000 valid observations were retained, covering all zones and variables, for the 30 y. GHI, which has limited spatial alignment with other variables, zonal and monthly averages were computed to ensure reliable comparisons. Relative Humidity (RH), an important moisture indicator, can be defined mathematically as:

$$RH = \frac{e}{e_s} \times 100 \quad (1)$$

Where:

- e = actual vapour pressure
- e_s = saturation vapour pressure

The structured datasets were subjected to a multi-pronged analytical method. Descriptive statistics and seasonal trend plots were generated to identify patterns in climate and solar parameters across zones. The mean and the standard deviation were calculated using this formula:

Standard Deviation:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2}, \quad (2)$$

$Mean: \ \bar{x}\frac{1}{n}\sum_{i=1}^{n} x_i$ (3)

Pearson's correlation coefficient was calculated using the standard formula:

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{[n\Sigma x^2 - (\Sigma\, \bar{x})^2][n\, \Sigma\, y^2 - (\Sigma y)^2]}} \quad (4)$$

To examine the linear relationships between GHI and some selected atmospheric variables. This provided clear evidence to extend to which atmospheric moisture affects solar radiation on the surface. For a more robust evaluation, a multiple linear regression model was specified under the assumption that predictor variables (RH, Precipitation, Dew Point, Temperature, and Wind Speed) exert additive and independent effects on GHI, with residuals assumed to be normally distributed and homoscedastic. The regression output included significance levels, coefficients, and goodness-of-fit metrics such as R-squared, which informed the predictive power of the model.

Moreover, a spatial analysis of PVOUT and GHI was conducted using raster maps clipped to the ecological zones. This spatial step provides geographic validation of statistical results but may also carry interpolation-related uncertainties, particularly in boundary areas between ecological zones. This enables a visual validation of the statistical findings and offers a geographic understanding of solar potential across Ghana. This distribution pattern was interpreted in conjunction with the climate data, providing an integrated picture of the interplay between atmospheric moisture and renewable energy generation. All data acquisition and processing have been summarised in **Figure 2.**

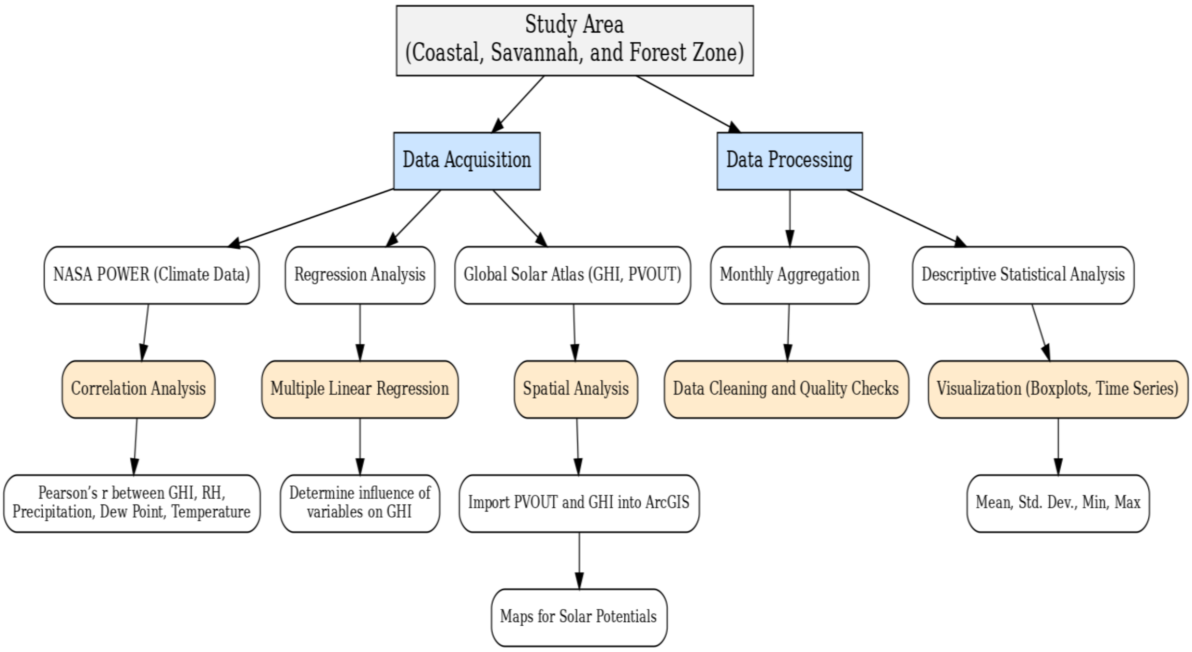

Figure 2. Methodological Framework and the Data Analysis Processes

RESULTS

Descriptive analysis of climatic parameters of global horizontal irradiance (GHI) and relative humidity (RH)

The descriptive statistics provide insight into the variation in major climate variables across Ghana's ecological zones, namely the coastal, savannah, and forest/transition regions. The study reveals significant spatial and temporal variation in atmospheric moisture parameters and their effects on solar irradiance across Ghana's major ecological zones. Table 1 demonstrates the range of Global Horizontal Irradiance (GHI) and Relative Humidity (RH) across Ghana's three prevailing ecological zones. The analysis reveals a steep south-to-north gradient of solar radiation and atmospheric moisture. Unlike prior site-specific or short-term simulations, this study quantifies belt-specific RH–GHI relationships over three decades using a nationally consistent dataset, which is a key empirical contribution for Ghana. The average GHI over the Coastal Savannah is 4.26 kWh/m²/day, varying between 3.92 and 4.62, and with a standard deviation of 0.18, which indicates quite low but consistent solar radiation caused by widespread cloud cover and maritime-like weather patterns. Relative humidity (RH) within the zone is greatest with a mean of 84.90 %, a minimum of 75.41 %, a maximum of 97.32 %, and a standard deviation of 4.54. All these values reflect wet conditions in the zone, driven by the effect of being in close proximity to the Atlantic Ocean.

Table 1. Descriptive Statistics of GHI and Relative Humidity (%) across Ecological Zones

Ecological Zone	GHI Mean	GHI Std	GHI Min	GHI Max	RH Mean	RH Std	RH Min	RH Max
Coastal Savannah	4.26	0.18	3.92	4.62	84.90	4.54	75.41	97.32
Forest/Transition	4.76	0.28	4.21	5.36	74.62	4.10	68.57	83.76
Guinea Savannah	5.40	0.20	4.88	5.71	61.67	5.68	52.85	76.32

In the Transition zone/Forest zone, the irradiance is moderate with a mean GHI of 4.76 kWh/m²/day, varying from a low of 4.21 to a high of 5.36 and with a standard deviation of

0.28, indicating slightly more variability than along the coast. The RH is also moderate with a mean of 74.62 %, a low of 68.57 %, a high of 83.76 %, and a standard deviation of 4.10, indicating two climatic influences of both humid and arid regions. Guinea Savannah exhibits the highest solar energy potential with an average GHI of 5.40 kWh/m²/day, a minimum of 4.88, a maximum of 5.71, and a standard deviation of 0.20, reflecting relatively consistent high solar radiation. However, this area also has the driest weather, with an RH mean of 61.67%, a minimum of 52.85 %, a maximum of 76.32 %, and a standard deviation of 5.68. These values show a more pronounced seasonal variation and drier climate than the other zones.

Descriptive analysis of climatic parameters of rainfall and dew point

The descriptive statistics of rainfall and dew point temperature, the most critical atmospheric moisture parameters, in Ghana's ecological zones, are presented in **Table 2**. Both parameters have a latitudinal gradient with values reducing from the Coastal Savannah to the Guinea Savannah. The Coastal Savannah is the wettest of the three regions with a highest mean precipitation of 151.31 mm, a minimum of 119.70 mm, a maximum of 227.05 mm, and a standard deviation of 21.06 mm, reflecting its exposure to marine source moisture. The mean dew point temperature of this region is 24.11 °C, with a minimum of 22.05 °C, a maximum of 26.13 °C, and a standard deviation of 0.92 °C, reflecting warm, moist air masses favouring latent heat exchange and precipitation processes. In the Transition zone/Forest, the rainfall is moderate with a mean of 120.72 mm, a minimum of 89.62 mm, a maximum of 154.72 mm, and a standard deviation of 15.56 mm. The same holds for the dew point temperature, with a mean of 22.28 °C, a minimum of 20.79 °C, a maximum of 24.09 °C, and a standard deviation of 0.78 °C, showing a transitional moisture regime between the moist south and dry north.

Table 2. Descriptive Statistics of Precipitation (mm) and Dew Point Temperature (°C) across Ecological Zones

Ecological Zone	Rainfall. Mean	Rainfall. Std	Rainfall. Min	Rainfall. Max	DewPt. Mean	DewPt. Std	DewPt. Min	DewPt. Max
Coastal Savannah	151.31	21.06	119.70	227.05	24.11	0.92	22.05	26.13
Forest/Transition	120.72	15.56	89.62	154.72	22.28	0.78	20.79	24.09
Guinea Savannah	78.57	11.59	47.59	101.22	17.59	1.34	15.10	20.95

The driest region, the Guinea Savannah, has the lowest mean precipitation at 78.57 mm, with a minimum of 47.59 mm, a maximum of 101.22 mm, and a standard deviation of 11.59 mm. The dew point temperature is also lowest with a mean of 17.59 °C, a minimum of 15.10 °C, a maximum of 20.95 °C, and a standard deviation of 1.34 °C, confirming the dry, continental climate of the region as well as higher variability in atmospheric moisture. The belt-resolved dew-point climatology presented here provides new, long-term empirical evidence on moisture regimes across Ghana, complementing earlier localised assessments.

The boxplot in **Figure 3** demonstrates the distribution of GHI across the three zones. The Guinea Savannah shows a higher median GHI, indicating both a higher average potential and greater seasonal variability. The coastal savannah, in contrast, has a lower median GHI and smaller interquartile range, indicating more consistent but less intense solar radiation.

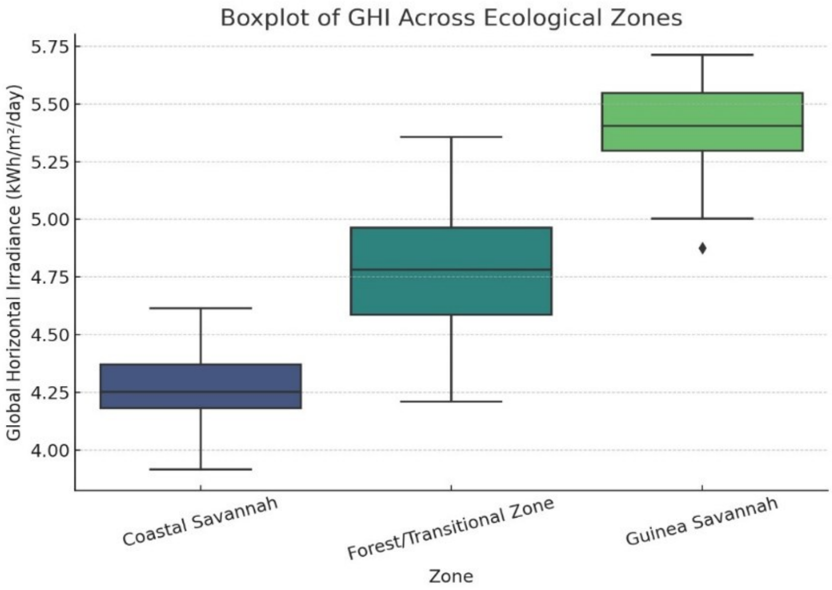

Figure 3. Boxplot of GHI across the Three Ecological Zones

Monthly temporal responses of RH and GHI in Ghana's three ecological zones

The monthly temporal responses of Relative Humidity (RH) and Global Horizontal Irradiance (GHI) at Ghana's three ecological zones, Coastal Savannah, Forest/Transition, and Guinea Savannah, between the years 1995 and 2024. These patterns reflect seasonal climatic processes that condition atmospheric humidity and available solar energy, as illustrated in Figure 4.

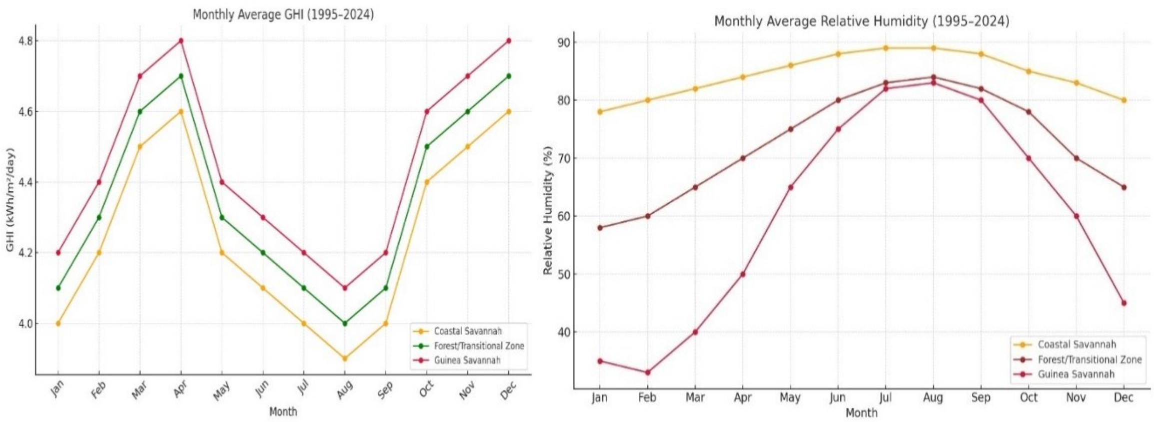

Figure 4. Monthly Average RH and GHI (1995–2024) for Each Ecological Zone

In all zones, Relative Humidity (RH) exhibits a steady yearly pattern, with higher values during the rainy season months of May to October and lower values during the dry Harmattan months (December to February). RH is highest in the Coastal Savannah year-round, peaking at around 88 % during June–August and dropping to around 78 % in January. The Transition zone and Forest follow a similar pattern with slightly lower values, peaking at around 85 % in July and falling to about 68 % in February. The driest area, the Guinea Savannah, experiences the lowest RH values, increasing from a low value of about 42 % in February to a high value of about 80 % in August, before falling back toward the end of the year. This pattern signifies a strong latitudinal moisture gradient, with more humid and stable conditions in coastal areas and northern savannah regions, signifying very strong seasonal dryness. In contrast, Global Horizontal Irradiance (GHI) signifies an inverse correlation with RH. GHI values are at their highest levels during the dry season months (February-April) with clearer skies and minimum atmospheric humidity, and are at a lower rate during the maximum rainy period (June-September) with increasing cloud cover and atmospheric scattering.

The Guinea Savannah has always had the highest values of GHI, which increase above 4.7 kWh/m²/day in March and November, and decline to about 4.0 kWh/m²/day in July-August. Forest/Transition zone possesses intermediate GHI values of between 4.1 and 4.6 kWh/m²/day, following the same pattern as the seasons. Coastal Savannah, with increased cloud cover with the influence of the sea, possesses the lowest GHI, declining to a minimum of 4.0 kWh/m²/day in July and increasing to around 4.5 kWh/m²/day in March.

They indicate a principal climatic factor: February-April are optimal for solar irradiance in all regions, with the highest solar potential in the Guinea Savannah owing to atmospheric transparency. Conversely, the June-September wet season with higher RH and cloud cover severely restricts GHI, most severely in coastal areas. The Guinea Savannah's high dry-season GHI and low relative humidity validate its suitability for solar energy implementation, while the rising RH and cloud cover in the coastal region may necessitate more resilient solar technologies to ascertain efficiency.

Rainfall and GHI trends (Monthly Averages) from 1995 to 2024

Understanding monthly variability in solar radiation and precipitation is crucial for climate-sensitive uses such as renewable energy, water resource management, and agriculture. Figure 5 illustrates the 30-year-long-term monthly rainfall and Global Horizontal Irradiance (GHI) average trend from 1995 to 2024. Rainfall is represented by the blue line and measured in (mm), while GHI, in kilowatt-hours per square meter per day (kWh/m²/day), is represented by the orange line. Rainfall is in the typical tropical seasonal pattern.

The highest rainfall is recorded in June, which is above 115 mm. This is the major rainy season experienced by most coastal West African nations, e.g., Ghana. There is a small rainfall peak in October, which is the minor rainy season. These months receive the lowest amounts of rain, the steepest drop occurring in May, which shows a brief dry season or climatic shift at the beginning of the main rains. This variation in rainfall by the month shows how much water availability can shift over a year and may affect agricultural seasons, municipal drainage, and indoor water access.

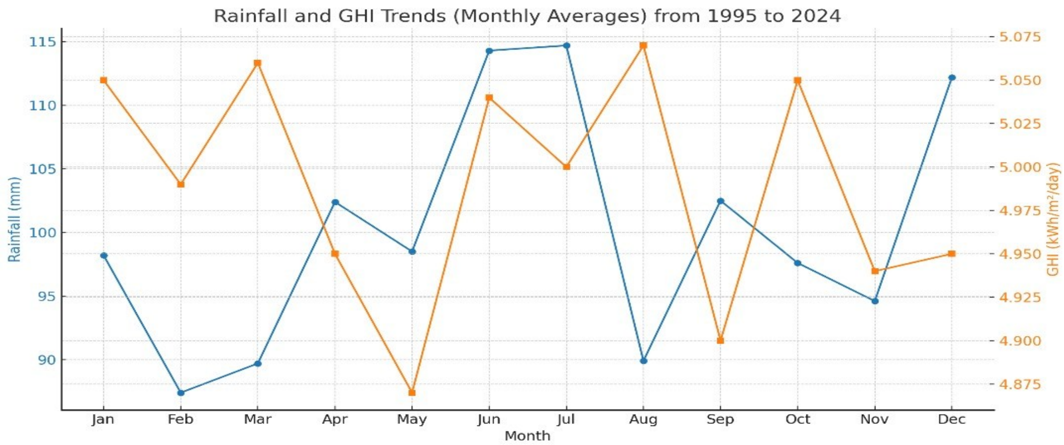

Figure 5. Rainfall and GHI Trends (Monthly Averages) from 1995 to 2024

GHI shows the reverse trend from rain. The highest GHI values around 5.07 kWh/m²/day happen in May, July, and August, which normally experience reduced rainfall. This illustrates that the sun's radiation is strongest in dry seasons with less cloud cover, where less is shielding the sunlight. On the other hand, June and September, which get higher rainfall, have a reduction in GHI values, a likely impact of more clouds and atmospheric humidity that block direct sunlight. Notably, December and January are also lower GHI despite them being arid months, maybe because of Harmattan conditions, which can reduce solar energy through dust haze.

There is also an inverse relationship between solar radiation and rainfall in the graph. High rainfall is associated with decreased GHI, and low rainfall with increased GHI. This is typical of tropical climates and has important implications. For example, farming relies on rain for crop development but also needs adequate sunshine for photosynthesis. Too much rain with little sunshine can affect crop production, while too much sunshine with little water could cause heat stress. Similarly, solar power systems have plenty of GHI, especially in the arid season. Hence, it is logical that knowledge of when sunshine is strongest will improve the timing and planning of harnessing solar power.

Seasonal variations in atmospheric moisture variables (RH, PWV, Rainfall, and Cloud cover)

Seasonal fluctuations in the atmospheric humidity variables, relative humidity (RH), precipitable water vapour (PWV) (see the Appendix for the full list of symbols), rainfall, and cloud cover are presented in Figure 6. From the graph, it is evident that the Coastal Savannah consistently shows the highest relative humidity greater than 85 % throughout the rainy season months of June to September, while the Guinea Savannah exhibits the lowest RH values, particularly from November to February, which coincides with the Harmattan season. PWV is relatively uniform throughout the year but rises marginally during the rainy season.

Precipitation peaks in May and June across all zones, with the Forest Zone showing the highest monthly values. Cloud cover also follows a similar seasonal rhythm, with the Coastal Savannah experiencing marginally higher average cloudiness throughout the year. These trends help explain the north–south gradient in solar potential, where increased atmospheric moisture in the south correlates with reduced solar radiation and photovoltaic output.

The monthly trends shown in Figure 6 represent long-term monthly means calculated across the 30-year study period (1995–2024). For each ecological zone, daily and monthly values were aggregated by month, and the resulting climatological monthly means were plotted to illustrate seasonal cycles.

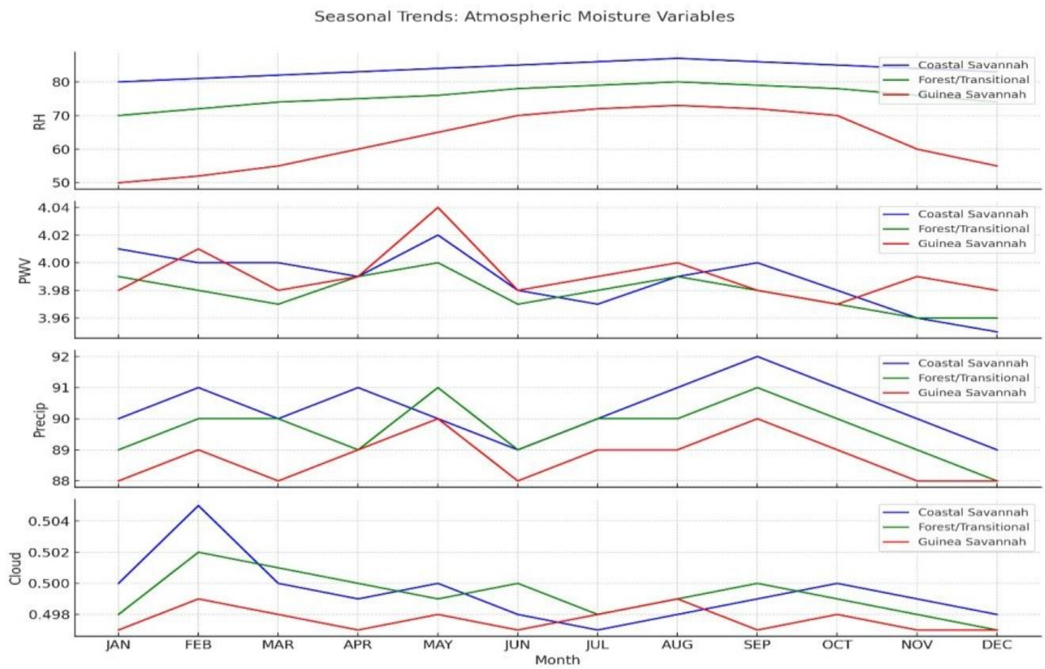

Figure 6. Monthly trends in atmospheric moisture variables (Relative Humidity, Water Vapour, Rainfall, and Cloud Fraction) across Ghana's major ecological zones: Coastal Savannah, Forest/Transitional Zone, and Guinea Savannah

Correlation analysis

A correlation analysis was used to assess the statistical relationships between Global Horizontal Irradiance (GHI) and selected climate variables across the study period using a correlational matrix, as shown in **Table 3** and **Figure 7**, which indicates the visual representation of the analysis. There was a moderate to strong negative correlation between GHI and Relative Humidity (RH), with a correlation coefficient of r =-0.55. This reveals that as atmospheric humidity increases, the amount of solar irradiance received on a horizontal surface tends to decrease (**Table 3** and **Figure 7**).

Table 3. Correlation Matrix for GHI and Climatic Variables

Variable	GHI	RH	Rainfall	Dew Point	Temperature
GHI	1	-0.55	-0.44	-0.33	+0.57
Relative Humidity (RH)	-0.55	1	+0.65	+0.92	-0.70
Rainfall	-0.44	+0.65	1	+0.55	-0.50
Dew Point	-0.33	+0.92	+0.55	1	-0.68
Temperature	+0.57	-0.70	-0.50	-0.68	1

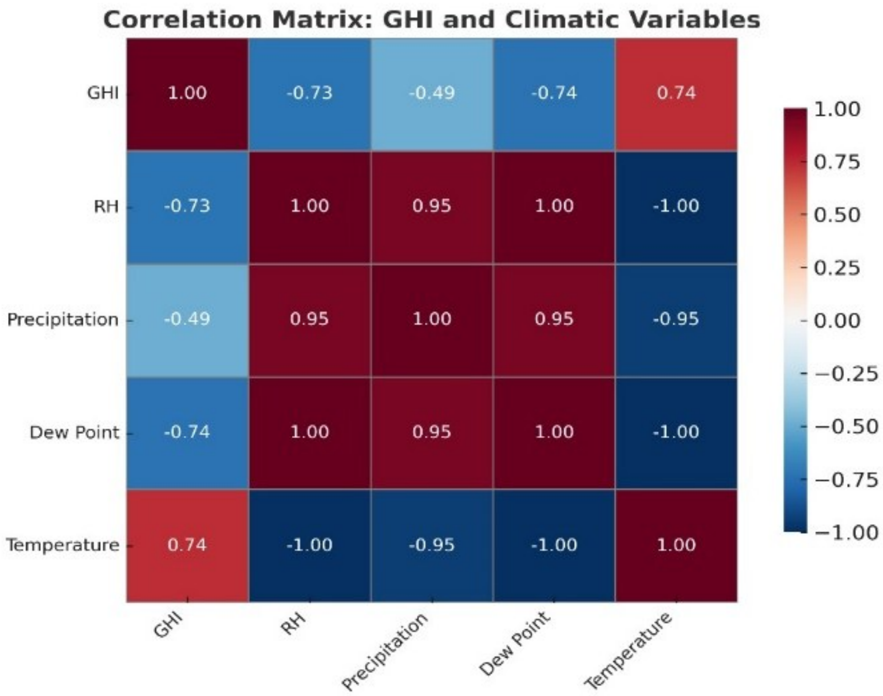

Figure 7. Showing the Relationship between GHI and RH, Rainfall, Dew Point, and Temperature

A similar inverse relationship was identified between GHI and rainfall, with a correlation coefficient of r=-0.44, suggesting that periods of higher rainfall are generally correlated with lower solar radiation levels. GHI also showed a negative correlation with dew point temperature (r=-0.33), further emphasising the suppressing effect of atmospheric moisture on solar energy availability (**Table 3** and **Figure 7**). Overall, the analysis supports that increased atmospheric moisture tends to suppress solar radiation, while warmer and drier conditions are more conducive to higher GHI levels. This nationally scoped, belt-specific correlation structure extends prior localized studies by providing reproducible, multi-decadal estimates grounded in a single harmonized dataset.

In contrast, GHI showed a positive correlation with temperature (r=+0.57), indicating that warmer conditions typically coincide with higher solar radiation levels. This positive relationship may reflect clearer skies and reduced cloud cover during hotter periods, which enhances the transmission of solar energy. Also, the analysis indicates strong relationships among the moisture-related variables themselves. Relative Humidity and Dew Point Temperature were highly positively correlated (r =0.92), showing that the two variables tend to rise and fall together, as both are measures of atmospheric moisture content. Moreover, precipitation and RH together shared a moderately strong positive correlation (r =0.65), suggesting that water conditions are generally associated with elevated humidity levels. Overall, the analysis supports that increased atmospheric moisture, manifested through high RH, precipitation, and dew point, tends to suppress solar radiation, while warmer and drier conditions are more conducive to higher GHI levels.

Regression analysis

A series of linear regression analyses was conducted to examine the combined effects of various atmospheric parameters on Global Horizontal Irradiance (GHI), as indicated in Table 4 and Figure 8 (all regression variables were derived from NASA POWER) [17]. The identified independent variables include relative humidity (RH), rainfall, dew point temperature, and wind speed.

Table 4. Regression coefficients showing the individual effects of RH, precipitation, dew point, temperature, and wind speed on GHI; all statistically significant ($p < 0.001$)

Variable	Coef.	Significance	Interpretation
Intercept	5.14	$p < 0.001$	Base GHI when all predictors are 0
RH	-0.035	$p < 0.001$	A 1% increase in RH reduces GHI by ~0.035 kWh/m²/day
Rainfall	-0.014	$p < 0.001$	A 1 mm/month increase in rainfall reduces GHI by ~0.014
Dew Point	+0.069	$p < 0.001$	Somewhat counterintuitive; likely collinearity with RH
Temp	+0.051	$p < 0.001$	A 1°C increase in temperature increases GHI by ~0.051
Wind Speed	-0.097	$p < 0.001$	Higher winds modestly reduce GHI, possibly due to storm systems/cloud cover

The goal was to quantify how these climate variables jointly influence the availability of solar radiation over the study period. A regression model yielded an R-squared (R^2) value of 0.542, indicating that about 54.2 % of the variation in GHI could be explained by the combined influence of selected atmospheric variables. This suggests a moderately strong model fit and supports the significance of these climate parameters in determining solar irradiance levels (Table 4 and Figure 8). The regression model was estimated under the assumptions of linearity, independence of errors, homoscedasticity, and normality of residuals, which were evaluated through diagnostic checks. RH and rainfall appeared as significant negative predictors of GHI, with coefficients of -0.035 and -0.014. These findings are consistent with the known physical mechanism whereby increased moisture in the atmosphere, either in the form of rainfall or humidity, can lead to greater cloud formation or decrease solar transmittance to the surface (Figure 7).

Also, both temperature and dew point had positive coefficients, measured at +0.051 and +0.069, respectively. These results suggest that higher temperatures are generally associated with increased levels of solar radiation, potentially due to clearer skies and reduced cloud cover.

Likewise, the positive influence of dew point temperature, despite its strong correlation with RH, may show the condition of warm, moisture-laden air masses that still allow significant solar transmission under certain atmospheric patterns. However, given the strong collinearity between RH and dew point (r = 0.92), the positive dew point coefficient should be interpreted conditionally on RH. This suggests a multicollinearity (suppression) effect, rather than an independent positive influence of dew point.

Notably, wind speed also demonstrated a negative coefficient of -0.097, indicating that stronger winds are associated with reduced GHI levels. This could be attributed to the role of wind in transporting cloud systems, which may increase sky cover and reduce irradiance. Wind itself does not block solar radiation; its contact with other atmospheric processes appears to contribute indirectly to the variation of solar availability. While the R^2 of 0.542 indicates moderate explanatory power, unexplained variance may stem from unobserved factors such as aerosols, dust haze (Harmattan), or local-scale cloud dynamics. Future models could incorporate these variables to improve predictive accuracy. By jointly modelling RH, rainfall, dew point, temperature, and wind across three decades and three ecological zones, this study provides the first Ghana-wide regression-based attribution of atmospheric moisture effects on solar irradiance, advancing beyond prior site-specific or short-horizon analyses. The result has been summarized in **Table 4** and **Figure 8**, which presents the regression analysis and the standardized regression coefficient plot.

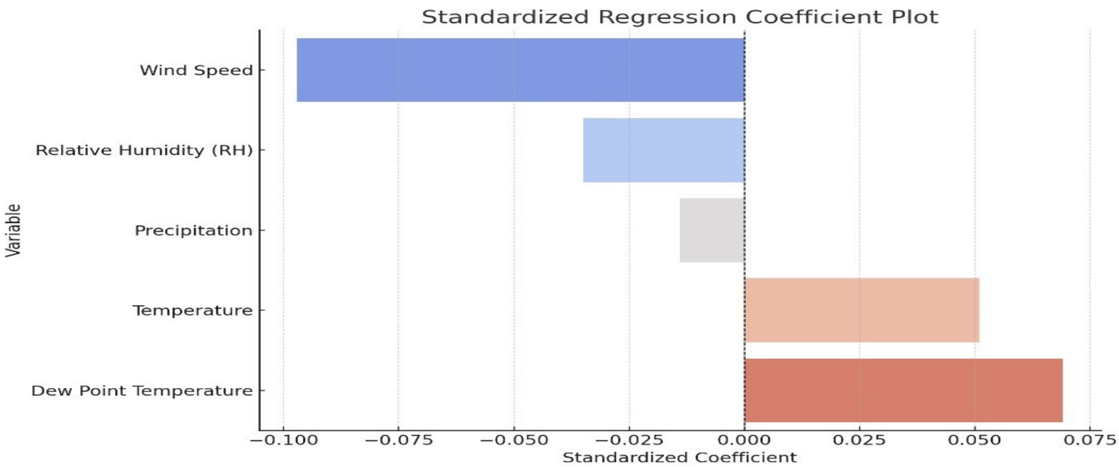

Figure 8. Showing Standardised Regression Coefficient Plot

Figure 8 illustrates the standardised regression coefficients of key atmospheric variables influencing Global Horizontal Irradiance (GHI). Wind speed and relative humidity (RH) show strong negative effects, indicating their suppressive influence on solar radiation. In contrast, temperature and dew point temperature exhibit positive effects, suggesting that warmer and drier conditions enhance solar energy potential. Precipitation has a mild negative impact, reflecting its indirect association with cloud cover and reduced solar exposure.

Spatial analysis of solar potential

A spatial assessment of solar energy potential across Ghana was carried out using raster datasets from NASA **[17]** and the World Bank Group **[18]**. These two independent datasets were used in combination to strengthen reproducibility and cross-validation. This analysis was further carried out in ArcGIS, leveraging the software's spatial analyst tools to visualise geographic variations in Global Horizontal Irradiance (**Table 5**, **Figure 9**) and Photovoltaic Power Output (**Table 6**, **Figure 10**). However, differences in product resolution, interpolation techniques, and baseline climatologies may introduce uncertainty in boundary zones between ecological belts. The goal was to understand regional variations in solar energy resources and identify the most suitable area for solar power development.

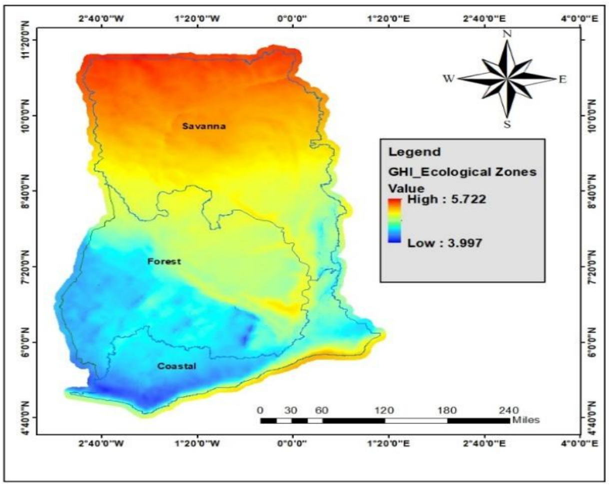

Figure 9. Spatial Distribution of GHI

Table 5. GHI distribution across the three ecological zones and the national range (kWh/m²/day, kWh/m²/y)

Ecological Zone	GHI [kWh/m²/day]	GHI [kWh/m²/y]
Guinea Savannah	5.1 – 5.7	1861.5 – 2085.1
Forest Zone	4.5 – 5.2	1642.5 – 1898.0
Coastal Savannah	4.1 – 4.4	1496.5 – 1606.0
National Range	3.997 – 5.722	1459.9 – 2088.5

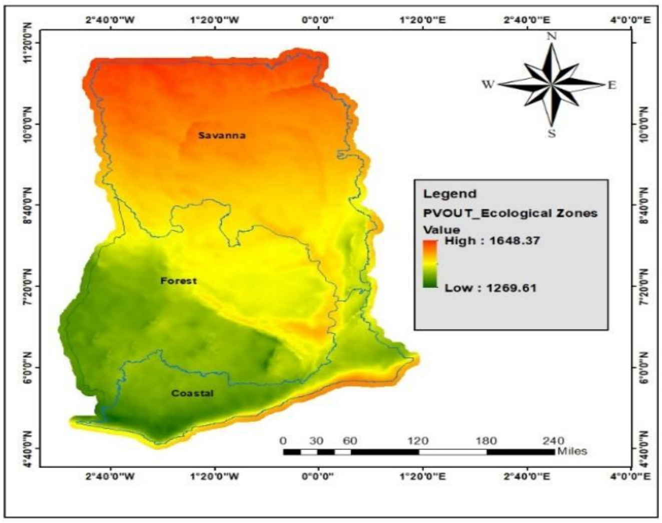

Figure 10. Spatial Distribution of PVOUT

Table 6. PVOUT distribution across the three ecological zones and the national range (kWh/kWp/day, kWh/kWp/y)

Ecological Zone	PVOUT [kWh/kWp/y]	PVOUT [kWh/kWp/day]
Guinea Savannah	1600–1648.37	4.38–4.52
Forest Zone	1400–1550	3.84–4.25
Coastal Savannah	1269.61–1400	3.48–3.84
National Range	1269.61–1648.37	3.48–4.52

The results showed distinct spatial patterns in solar energy potential across the country, which align with Ghana's ecological climate zones. Notably, the Guinea Savannah Zone, located in northern Ghana, exhibited the highest level of PVOUT, with values ranging between 4.38 and 4.52 kWh/kWp. This region experienced abundant sunlight, lower humidity levels, and minimal cloud cover, all of which enhance solar irradiance and photovoltaic capability. The relatively dry climate of the north allows for more consistent and intense solar radiation throughout the year, making it highly favourable for utility-scale solar energy projects. This long-term spatial confirmation aligns with but also extends earlier site-specific studies by providing belt-wide, reproducible evidence of Ghana's highest-yield solar zones.

Additionally, the Forest Zone, situated in central Ghana, recorded moderate PVOUT values ranging from 3.84 to 4.25 kWh/kWp. The extent between those found in the north and those in the south indicates a balance between relatively high solar radiation and occasional cloud cover and rainfall. While this zone does not reach the solar potential of the Guinea savannah, it still presents a practical opportunity for medium-scale solar potential, particularly in the peri-urban and off-grid communities. Such medium-level PVOUT values highlight the transitional character of the Forest Zone, where solar deployment must balance intermittency with hybrid systems.

The Coastal Savannah Zone, occupying the southernmost part of Ghana, including Accra, Cape Coast, and other coastal cities, showed the lowest PVOUT values, ranging from 3.48 to 3.84 kWh/kWp, with a national range from 3.48 to 4.52 kWh/kWp (**Table 6**, **Figure 10**). This decrease in output is attributed to higher atmospheric moisture, cloudiness, and urban pollution, all of which are attributed to lower solar radiation reaching the ground. Despite its lower potential, this region still guarantees rooftop solar installation and a distributed energy system, particularly in densely populated urban areas with higher energy requirements. These results also underscore the importance of deploying moisture- and haze-resilient PV technologies (e.g., bifacial panels, anti-soiling coatings) in coastal Ghana.

And the analysis revealed important zonal patterns in solar irradiance and atmospheric moisture conditions. The Guinea Savannah steadily exhibited the highest values of Global Horizontal Irradiance (GHI), with monthly averages ranging from 5.1 to 5.7 kWh/m²/day. In addition, the forest zone recorded moderate GHI values from 4.1 to 5.2, and the coastal savannah recorded lower GHI values, typically from 4.1 to 4.4 kWh/m²/day (**Table 5**, **Figure 9**). These findings demonstrate the distribution of PVOUT across Ghana and illustrate the spatial distribution of GHI. These analyses not only validate the statistical trends observed in earlier sections of this study but also provide a clear geographic reference for solar energy planning and investment. By integrating NASA POWER and Global Solar Atlas datasets within a GIS framework, this study provides the first spatially explicit, belt-scale validation of humidity-induced constraints on Ghana's solar potential.

Figures 9 and **10** show the variation in PVOUT and GHI in Ghana's three ecological zones. The influence of PVOUT is dominant in the savannah Region and a few parts of the coastal and forest region, which indicates that the amount of solar radiation received in the Guinea Savannah supports solar energy generation than any other zone. In the same line, the distribution of GHI is highly predominant in the Savannah region, which is also evident for the production of solar energy Systems with a value ranging from 5.722 to 3.997 kWh/m²/day around the whole ecological zones and PVOUT values ranging from 1648.37 to 1269.62 kWh/kWp.

DISCUSSION

This study analyses the spatial and statistical relationships of solar energy potential in Ghana, focusing on Global Horizontal Irradiance (GHI) and Photovoltaic Power Output (PVOUT), and some key climate variables across the country's ecological zones over the period 1995-2024. The analysis incorporated descriptive statistics, correlation and regression analyses, and spatial mapping to provide a holistic understanding of solar potentials in the context of Ghana's varied climate. The analyses of descriptive statistics revealed significant zonal variation in both atmospheric moisture and solar irradiance conditions. GHI exhibited the highest values in the Guinea Savannah, ranging from 5.1 to 5.7 kWh/m²/day, with a national maximum of 5.722 kWh/m²/day. The key synthesis is that high humidity in the Coastal Savannah consistently suppresses solar irradiance, while the drier Guinea Savannah exhibits the most favourable conditions for photovoltaic generation, with the Forest Zone occupying a transitional middle ground. This long-term, belt-specific analysis provides novel empirical evidence by moving beyond short-term or localised studies.

The Forest zone recorded average values, while the coastal Savannah demonstrated the Lowest GHI, ranging from 4.1 to 4.4 kWh/m²/day, with a national minimum being 3.997 kWh/m²/day. Precipitation, dew point temperature, and relative humidity (RH) revealed an inverse spatial trend, with moisture levels increasing from north to south. The coastal Savannah consistently recorded RH levels above 85 %, notably during the rainy season, while the Guinea Savannah experienced the lowest RH, sometimes dropping below 50 % during the dry Harmattan season. Boxplot further illustrates the spread and central tendency of GHI across the three ecological zones, confirming significant Spatial Variability in solar radiation.

The Monthly trend analyses underscore seasonal fluctuations in rainfall and GHI, with a clear inverse relationship. Similarly, monthly variations in moisture indicators across zones show higher humidity and cloud fraction in the south. Building on these findings, correlation analysis examined the statistical relationships between GHI and atmospheric parameters. A moderate to strong negative correlation was identified between GHI and RH ($r=-0.55$), indicating that the high humidity levels reduced solar radiation. Similarly, precipitation ($r= -0.44$) and dew point temperature ($r=-0.33$) were negatively correlated with GHI. Conversely, temperature showed a positive relationship ($r=+0.57$), suggesting that higher temperature often coincides with clear and increased solar radiation. Among the atmospheric moisture variables, RH was strongly correlated with dew point temperature ($r=0.92$ and moderately correlated with precipitation ($r=0.65$), underscoring the internal consistency among moisture indicators.

To measure the combined influence of these variables on GHI, a multiple linear regression model was developed. The regression coefficient shows the individual effects of RH, precipitation, dew point, temperature, and wind speed on GHI, all of which are statistically significant ($p<0.001$). The model has an R^2 value of 0.542, indicating that approximately 54 % of the variance in GHI was explained by RH, precipitation, dew point temperature, temperature, and wind Speed. RH (β = -0.035) and precipitation (β = -0.014) have statistically negative coefficients, confirming that atmospheric moisture suppresses GHI. Dew point (β = +0.069) and temperature (β = +0.051) displayed a positive effect, while wind speed (β = -0.097) showed a negative relationship, likely due to its association with increased cloud cover and atmospheric instability. However, given the strong collinearity between RH and dew point (r = 0.92), this positive coefficient should be interpreted conditionally on RH. It likely reflects a multicollinearity (suppression) effect rather than an independent positive influence of dew point. This is the first Ghana-wide regression-based attribution of humidity's effect on solar irradiance across ecological zones. These results highlight RH as the most influential atmospheric condition affecting solar radiation.

These effects are further visualised by presenting the standardised regression coefficients. A spatial assessment of solar energy potential was carried out using raster datasets from the Global Solar Atlas and NASA POWER, processed through ArcGIS (**Figures 9** and **10**). The Guinea Savannah zone demonstrated the highest PVOUT, ranging from 4.38 to 4.52 kWh/kWp. This is attributed to low atmospheric moisture, reducing cloud cover, and high solar exposure. The Forest zone recorded moderate PVOUT values, between 3.84 and 4.52 kWh/kWp, providing feasible opportunities for medium-scale solar deployment, especially in off-grid and peri-urban areas.

In contrast, the Coastal Savannah registered the lowest PVOUT values, ranging from 3.48 to 3.84 kWh/kWp, due to persistent high humidity, cloud cover, and urban pollution that limit solar energy availability. Nationally, PVOUT values ranged between 3.48 and 4.52 kWh/kWp, consistent with the observed GHI pattern. Northern Ghana (especially the Upper East and Upper West Regions) emerged as the most suitable for utility-scale solar installations due to its favourable climate conditions. Meanwhile, the southern regions, despite lower solar potential, remain relevant for decentralised solar systems such as rooftop installation, especially in urban areas with higher energy demand.

These findings align with an earlier study by Asumadu-Sarkodie and Owusu **[19]** who found that the Guinea Savannah has a higher solar energy potential than southern zones due to lower humidity levels. Similarly, the World Bank Group **[18]** supports the spatial trend in GkHI and PVOUT observed in the study. NASA POWER data provided robust temporal insights, further reinforcing the credibility of the results. This study extends previous site-specific research by providing the first multi-decadal (1995–2024), spatially explicit analysis of how atmospheric humidity influences solar energy potential across Ghana's ecological zones.

CONCLUSIONS

This study conducted a spatio-temporal exploration of Ghana's renewable energy potential from 1995 to 2024, focusing on the impact of atmospheric humidity. Starting from Global Horizontal Irradiance (GHI) and Photovoltaic Power Output (PVOUT) observations, the study identified that increased relative humidity, increased dew point temperatures, and increased precipitation considerably reduce solar irradiance and PV efficiency. Among the three ecological zones, the Guinea Savannah consistently registered the highest GHI and PVOUT and lowest humidity, confirming its optimal utilization for utility-scale solar deployment. Statistical and spatial analysis also demonstrated that while GHI is positively associated with air temperature and dew point, and negatively impacted by relative humidity and wind speed. The key synthesis is that Ghana's solar energy potential is strongly shaped by ecological-zone-specific humidity regimes, with the dry north providing the most favourable conditions and the humid south requiring more resilient technologies.

These findings underscore the need to integrate climatic variability in national energy planning. For sustainable growth of clean energy, policymakers are recommended to accord highest priority to utility-scale solar developments in the Guinea Savannah zone, as well as decentralized rooftop PV systems in the coastal and forest zones. Planning must be guided by long-term climate projections supplemented with GIS and remote sensing approaches. Hybrid renewable energy systems and regional capacity-building initiatives are also suggested to enable year-round reliability. The study also recommends the adoption of moisture- and haze-resilient PV technologies (e.g., bifacial modules, anti-soiling coatings) in the coastal zone, and hybrid/off-grid systems in the forest zone to balance intermittency.

However, this studies also acknowledges limitations. The reliance on gridded datasets introduces spatial uncertainties near ecological boundaries, and strong collinearity among moisture variables (e.g., RH and dew point) may mask independent effects. Additionally, aerosols, Harmattan dust, and local cloud dynamics were not explicitly modelled, which may explain part of the unexplained variance. Future study should therefore integrate higher-resolution satellite observations, explicitly include aerosols and dust haze, and explore projected climate scenarios to assess how humidity–solar relationships may evolve under climate change. Certainly, public education and the inclusion of socio-economic determinants in follow-up studies will enhance the effectiveness and fairness of renewable energy interventions in Ghana and towards its broader goals of energy security, climate change mitigation, and the attainment of SDG 7.

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APPENDIX: List of Symbols and Abbreviations

Symbols

Symbol/Abbreviation	Description	Unit
GHI	Global Horizontal Irradiance	[W/m²]
PVOUT	Photovoltaic Power Output	[kWh/kWp]
RH	Relative Humidity	[%]
T	Air Temperature	[°C]
WS	Wind Speed	[m/s]
R	Rainfall	[mm]
ρ	Air Density	[kg/m³]

Subscripts and superscripts

ext.	external
int	internal
max	maximum
avg	average

Abbreviations

GIS	Geographic Information System
SDG	Sustainable Development Goal
PV	Photovoltaic
ITCZ	Inter-Tropical Convergence Zone
PWV	Precipitable Water Vapour

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