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Spatial and Temporal Solar Potential Variation Analysis in Uganda Using Measured Data

Daniel N Katongole[1,2*], Karidewa Nyeinga[2], Denis Okello[2], Daniel Mukiibi[2], James Mubiru[3] and Yeeko Kisira[4,5]

[1]Department of Physics, Gulu University, P.O. Box 166, Gulu, Uganda.
[2] Department of Physics, Makerere University, P.O. Box 7062, Kampala, Uganda.
[3] Civil Aviation Authority, Entebbe, P. O. Box 5536, Kampala, Uganda.
[4] Department of Geography, Geo-informatics and Climatic Sciences, Makerere University, P.O. Box 7062, Kampala, Uganda.
[5]Institute of Education and Lifelong Learning, Victoria University, P.O. Box 30866, Victoria Tower, Plot 1-13 Jinja Road, Kampala Uganda.
**Corresponding author, Email: d.k.nkwata@gu.ac.ug*
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Abstract

The paper presents an analysis of spatial and temporal solar potential variations in Uganda**.** The solar radiation potential distribution was investigated based on measured data from 56 ground meteorological stations across Uganda from January 2015 to February 2022. The data were recorded after every 5-minute interval. The monthly average daily Global Horizontal Irradiance (GHI) was analysed using the spatial inverse distance weighting (IDW) interpolation technique in ArcGIS 10.7.1. The GHI distribution was found to have maxima at equinox and minimum between June and July. The average global horizontal irradiation is found to be 1680 KWh per year, with a daily variability below 10%. This is above the threshold for solar energy applications and with such low variability, large scale solar PV plants can be installed with minimum backup requirements. Northern Uganda receives the highest average daily global horizontal irradiation of 5.38 Whm^{-2} day^{-1}, while Western Uganda receives 4.16 Whm^{-2} day^{-1}, the lowest. The average AM/PM ratio depicted a value above 2 for all regions in Uganda and therefore, optimal solar energy exploitation for fixed systems favours eastern orientation. The central, eastern and northern Uganda which is 69.3% of the country has relief favourable for large scale solar PV power plants and CSP facilities.

Keywords: GHI, IDW, Global solar radiation, Solar insolation, PV power plants, Uganda.

Introduction

Utilization of sustainable and renewable energy resources can considerably curtail major overhead costs while minimizing pollution at the same time (Mukherji et al. 2020, GOGLA 2019). With the supportive renewable energy policies since 2016, the Soroti solar power station (10 MW), Tororo solar power plant (10 MW), Kabulasoke solar PV (20 MW) and Mayuge solar plant (10 MW) with several community mini-grids (KW) have been commissioned across the country (ERA 2012, MEMD 2015, GIZ 2020, UOMA 2019, 2020). This is still less than 4% of the total electric power production as of 2021, but the projection is 5000 MW by 2040 (MEMD 2015, van der Ven 2020). Solar energy is globally playing tremendous roles in transforming livelihoods of rural communities without access to gridded power, of course with a host of carbon credit benefits (Zaman et al. 2021, ESI 2021). The performance of solar energy is grappling with climatic conditions yet, it is inexhaustible, clean, safe and one of the most viable and desirable green energy alternatives (Sengupta et al. 2021). Promotion of large-scale PV deployment requires accurate forecasting of PV power output, proper system reliability (Mubiru 2006, Shi et al. 2012) and mapping of the solar radiation resource (Bayray et al. 2021).

Solar electric power plants are steadily becoming globally popular and therefore knowledge of solar radiation patterns is crucial (Asumadu-Sarkodie and Owusu 2016). The impact of the solar radiation variability on the solar energy potential and the amount of energy that can be redeemed by replacing other sources with solar energy need be established. This will provide the much-needed alternative energy to boost economic development in full consideration of environmental protection values. Moreover, solar power generation is second to hydroelectric power (HEP) in contributing to the gridded electricity globally (Aarakit et al. 2021). Solar power generation is relatively new in Uganda; there are a limited number of large-scale power plants installed. Therefore, access to technical data in Uganda is restricted where available (Widodo et al. 2018, Oloya et al. 2021).

Analyzing annual meteorological patterns and how they affect solar irradiance at any location is crucial to solar PV power plant performance (Abdelkader et al. 2010, Ajitha et al. 2019). The best and most accurate source solar radiation data would be installation of measuring equipment, but the price, maintenance and calibration costs are prohibitively high. Solar radiation prediction using empirical methods (Mubiru 2006) demonstrates direct and indirect influence of geographical and weather conditions (Yazdani et al. 2016, Mubiru and Banda 2008). Rivington et al. (2005) and Uko et al. (2016) also reported the interdependence using sunshine duration. In Brunei Darussalam and Jaipur, India GHI is seen to depend linearly on atmospheric temperature and relative humidity (Yazdani et al. 2016, Mukherji et al. 2020). Rivington et al. (2005) proposed equations that demonstrate the interdependency between solar radiation, atmospheric temperature and relative humidity based on different climatic conditions (Coops et al. 2000, Mubiru and Banda 2008). Yao et al. (2014) established the Monthly Average Daily Global Solar Radiation (MADGSR) models and Daily Global Solar Radiation (DGSR) models using 42 years of local weather data in different weather conditions in Shanghai, China. Yadav and Chandel (2014) developed a model that presented the effects and variations of temperature, relative humidity and wind speed on the solar radiation pattern using ANN techniques (López et al. 2005, Mubiru 2008, Shi et al. 2012, Assi et al. 2013, Yadav and Chandel 2014, Bhattacharya et al. 2014). All these findings demonstrate that the daily variations in meteorological conditions both directly and indirectly influence the solar radiation patterns.

There are limited studies on assessment of solar radiation distribution in Africa and Uganda in particular. These studies used limited measured data possibly due to inadequacy of existing meteorological stations in collecting solar energy data (Mubiru et al. 2007, Eludoyin et al. 2014, Gustavsson 2015, Oloya et al. 2021) or lack of research culture.

Some authors have used such interpolation methods as; nearest point, moving average, moving surface, trend surface and ordinary Kriging using data from four stations (Mubiru et al. 2007, Biira and Kilama 2014), empirical correlations (Mubiru and Banda 2007, Mubiru 2006), regression with meteorological parameters (Karume et al. 2007), artificial neural networks (Mubiru 2006, Mubiru and Banda 2008, Mubiru 2008, Karoro a et al. 2011, Mubiru 2011, Mubiru and Banda 2012). Solar radiation maps for Uganda were developed by Mubiru and Banda (2012) using ANN with from a few locations for prediction. This could not account for the variabilities associated with local topographic conditions. Increasing the number of data stations and their spatial distribution can greatly improve results.

In this study, we analysed the spatial and temporal solar radiation distribution across the country using measured meteorological and geographical data collected from 56 meteorological stations in Uganda from January 2015 to February 2022. Results from this study will support in PV power plant designing, weather forecasting, climate risk information, local and national policy, planning and decision-making for sustainable development in agriculture, aviation and health.

Materials and Methods

Description of Uganda's regions

Uganda is located between coordinates 01° 30'S–04° 00'N and 29° 30'E–35° 00'E, occupying an area of about 241,500 km^{-2} , topographically characterized by plateaus, highlands, mountains, rolling hills, flat lands, rivers, lakes and wetlands (Mubiru et al. 2007). The study was based on Uganda's regional boundaries as shown in Figure 1 and summarized in Table 1.

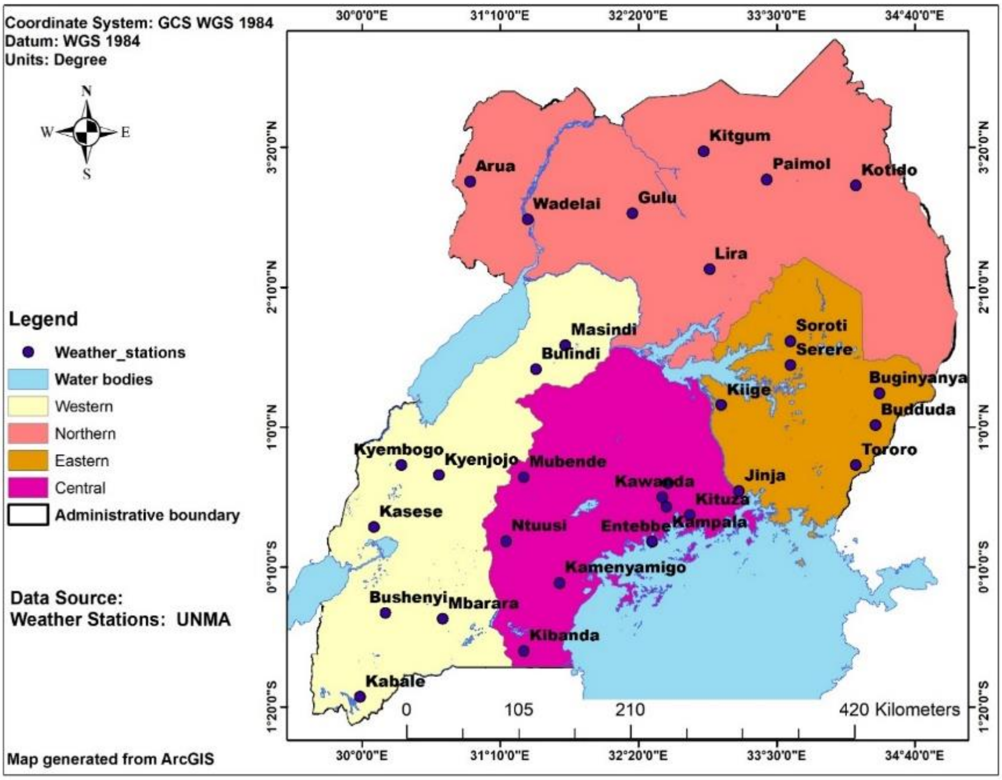

Figure 1: Map showing the regional distribution of the selected weather stations in Uganda (UBOS 2022).

Table 1: Study area per sub-region

Sub region	Area (in km^2)	Average altitude (m above sea level)
Northern	45,912.9	662–2719
Eastern	39,478.8	1121–1143
Central	61,403.2	1,200–1265
Southwestern	55,276.6	1,276–1473

Equipment and data collection

Data was obtained from the 56 Trans-African Hydro-meteorological Observatory (TAHMO) weather stations run by the Uganda National Meteorological Authority (UNMA). It is a network of weather stations across Africa. Each of these stations consists of an ATMOS 41 sensor suit and an EM60G data logger (Figure 2). Each of the sensor suits is an all-in-one weather station with sensors that continuously monitor standard weather measurements. The data logger captures data with site specifications at various intervals in real-time, stores and uploads it on online where it can be accessed by authorized personnel. The uncertainties in GHI and precipitation data ±5%, relative humidity, wind gust and wind speed data is ±3%. The uncertainties in average air temperature and barometric pressure, ±0.6% and ±0.1 kPa from –10 to 50 °C and ±0.5 kPa from –40 °C to 60 °C, respectively.

Figure 2: Typical TAHMO weather station.

Other data were obtained from Makerere University and solar PV power stations. Data was also collected from ADCON Telemetry, EU-PVGIS and CM-SAF databases for comparison. The measured data was compared with satellite data for consistency and periods of missing data were teased out.

Analysis of temporal variation and spatial distribution

The spatial GHI data analysis was done using the average value at each latitude and longitude, prepared by ArcGIS 10.7.1 software. This was then interpolated using the spatial inverse distance weighting (IDW) interpolation technique in ArcGIS 10.7.1. The average GHI value was then classified using the software spatial analyst tool and plotted with colour maps to show the spatial variations within the boundaries of Uganda (Fillol et al. 2017). Using the IDW interpolation technique closer objects are more alike than those far apart. Measured values close to unmeasured location are used to predict the unmeasured value. The technique assumes that each measured point has a local influence that diminishes with distance (Emmendorfer and Dimuro 2020, Liu et al. 2021). The IDW interpolation of a value $\hat{y}_j$ for a given location j was computed using Eq. 1:

$$\hat{y}_j = \sum_{i=1}^{n} w_{i,j} y_i \qquad (1)$$

Where each $y_i, i = 1, \cdots, n$ is a data point available at a location i. The weights $w_{i,j}$ for each data point are defined by Eq. 2:

$$w_{i,j} = \frac{d_{i,j}^{-\alpha}}{\sum_{k=1}^{n} d_{k,j}^{-\alpha}} \qquad (2)$$

$d_{i,j}$ being the Euclidean distance between a data point at location i and the estimated data at location j; n is the number of available data points; the power α = 2 is a control parameter, and it is the most commonly adopted value (Liu et al. 2021). Descriptive statistics of the monthly daily values were presented in tables, graphs and maps.

Analysis of solar energy potential and spatial-temporal variation indicators

The solar energy potential of a location was analysed using GHI maps in ArcGIS 10.7.1 environment basing on latitude and longitude. Using colour maps and applying the weighted overlay tool in ArcGIS, ratings for each criterion from 1 (less suitable) to 9 (highly suitable) were used to classify the country into categories of low, medium and high suitability. The overall technical solar energy potential for the country was done basing on areas with medium and high aggregated suitability ratings (Mahmud et al. 2014, Bayray et al. 2021). Slope analysis was done using a Uganda 30 meters SRTM Digital Elevation Model (DEM), obtained from the open source at Regional Centre for Mapping of Resources for Development (RCMRD 2018). The data was prepared in ArcGIS 10.7.1 for terrain analysis of slope. A slope elevation and road network maps were developed to analyse the land relative suitability indicators. Areas with slopes above 4% were teased out as not appropriate for large-scale solar PV installation. All the shape files for Uganda regional and administrative boundaries were sourced from Uganda Bureau of Statistics (UBOS 2022). Slope and altitude are significant limitations to effective solar harvest. Technical solar energy potential analysis was based on regional meteorological conditions, road network and availability of grid transmission lines.

Results and Discussion

Spatial-temporal variations of GHI in Uganda

Solar resource assessment based on GHI and DNI measurements was done using measured meteorological data spanning from 2015 to 2022 from 56 UNMA stations. Figures 3(a) to (d) show the regional average daily temporal variations of GHI and the summary in Table 2.

The annual GHI distribution trend is bimodal having maxima at equinox, while the lowest daily GHI reported in June and July. The average solar irradiation in Uganda is found to be 1680 KWh per year, and this is above the threshold for appropriate irradiation for a variety of solar energy applications. The decreasing GHI trend from March to April is enhanced by the onset of the rain season, characterized by high humidity and heavy cloud cover; negatively affecting GHI. The wide variations in solar irradiance across all regions for the same month arise from both the inclination angle and local weather conditions (Abdelkader et al. 2010). Uganda's equatorial positioning facilitates a fairly distributed GHI across the year, with slight differences across the country. Designing and sizing of a solar power conversion system requires knowledge of the GHI availability and hence the GHI potential at the location of interest (Shrestha et al. 2019).

Northern region

Comparatively, northern Uganda receives higher average daily GHI, stretching from 180.27 Wm^{-2} to 244.33 Whm^{-2}, which translates into an average of 5.16 $kWhm^{-2}$ day^{-1} (Figure 3a). The GHI values are higher in the north east and reduce west wards as shown in the maps in Figure 5(a) and (b). This is a fairly large amount when compared to countries like Japan, Europe, and the United States where deployment of solar technologies is effectively exploited (Jain et al. 2011). The sub-regional solar irradiance has maximum of 224.33 Wm^{-2} which happens during periods of equinox and only falls below sub regional average in June and July. Variations in solar radiation values are observed for similar months across the years. The sub regional; average daily maximum and minimum temperatures range from 30.2–31.9 °C and 18.0–19.8 °C, respectively, while the daily average temperature ranges between 25 °C and 25.8 °C (See Figure 5(b)).

Eastern region

The daily average GHI varies between 174.5 and 225.75 Wm^{-2} (Figure 4(a) and (b), with an average of solar irradiation of 4.94 $kWhm^{-2}$ day^{-1} (Figure 3(b)). The regional variation in GHI across stations is observed to have minimum temporal variations except for January and November. The average daily global radiation for the largest part of the year apart from June, July and August is found to be 4.47 kWm^{-2} day^{-1}, while the corresponding average daily maximum and minimum temperatures range between 29.4–31.1 °C and 17.1–18.9 °C, respectively as shown in Figure 5(a).

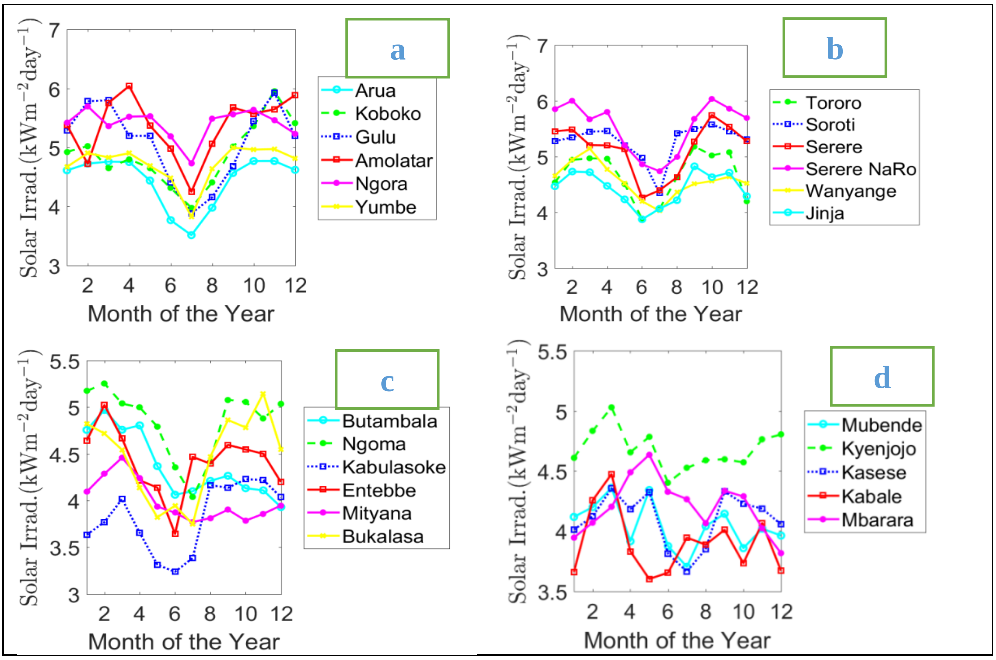

Figure 3: Regional variation of monthly average daily global solar irradiation on a horizontal surface across Uganda: (a) Northern, (b) Eastern, (c) Central, (d) Western Regions.

Table 2: Summary of average daily GHI values in Uganda according to region

Region	Minimum (Wm^{-2})	Maximum (Wm^{-2})	Mean (Wm^{-2})	Median (Wm^{-2})	Standard deviation (%)
Northern	180	244	215	217	9.0
Eastern	175	226	206	209	7.7
Western	150	195	174	176	8.0
Central	155	202	180	181	8.0

Central region

This region is around Lake Victoria basin and receives GHI between 155.35 Wm^{-2} and 201.98 $kWhm^{-2}$ which results into an average solar irradiation of 4.3 $kWhm^{-2}$ day^{-1} (Figure 3c). This is comparatively lower than the national average of 4.6 $kWhm^{-2}$ day^{-1} and also far lower than estimates from satellite data (Avellino et al. 2018). The low irradiance levels are also influenced by presence of atmospheric aerosols as a result of industrial pollution levels. The sub regional temperatures are moderate possibly due to the influence of the surrounding water great lakes. This needs further analysis as the Earth's solar radiation balance determines all long-term meteorological parameters and is affected by such human activities as industrialization, deforestation, overgrazing, un-checked greenhouse emission and the like.

Western region

Western Uganda comparatively receives GHI between 149.9 Wm^{-2} and 194.95 Wm^{-2}, which is results into an average irradiation of 4.2 $kWhm^{-2}$ day^{-1} (see (Figures 3(d), 4(a) and (b)) which the lowest in Uganda. The region is characterized by high altitudes owing to hilly surfaces as shown by the map in Figure 7(a). This value reduces to the tune of 3.60 $kWhm^{-2}$ day^{-1} from June to August which is far below the estimated national average. The monthly daily average maximum and minimum temperature varies between 25.2–26.9 °C and 13.6–16.3 °C, respectively, while average daily temperature is between 20.7 to 22.4 °C as shown in Figure 5(b).

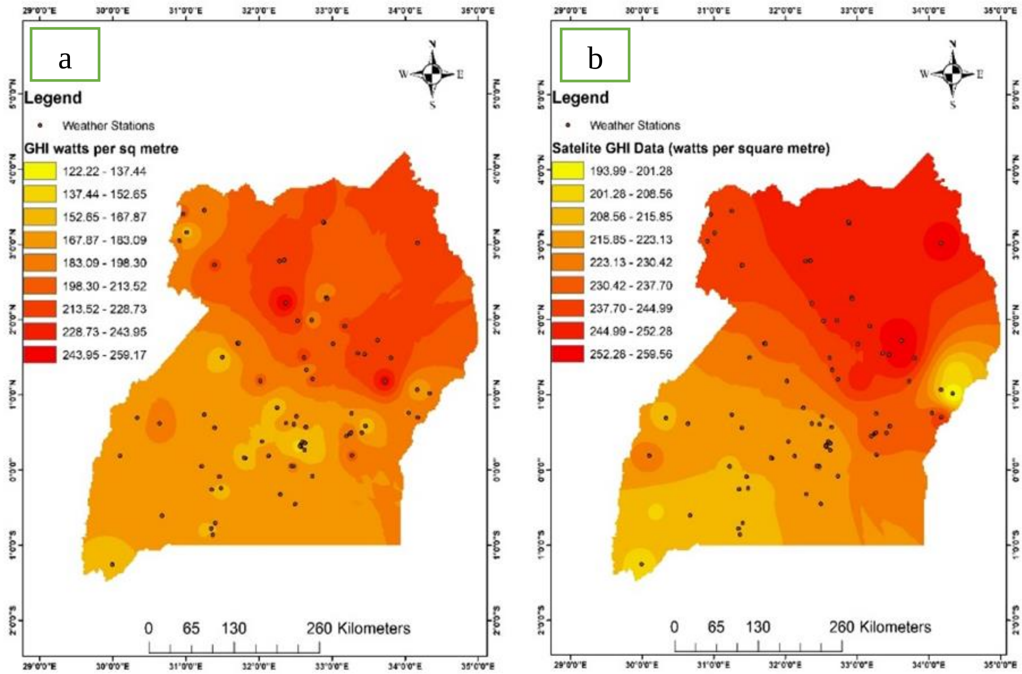

Figure 4: Average daily GHI distribution (a) Measured data, (b) Satellite data from January 2015–February 2022.

Spatial variations

The solar potential and the operability of the solar irradiance resource in Uganda have been analysed and estimated using the inverse distance weighting (IDW) interpolation method in ArcGIS 10.7.1. The interpolation maps were estimated basing on 5-minute data intervals, with a spatial resolution of 2417.49 m × 2417.49 m. The resulting time series allowed the mapping of the daily average values. The indicator maps were created to identify the GHI potential, operational areas with a slope less than 4%, and the inter-day solar radiation variability.

GHI and DNI potential

The developed colour maps show both the average measured and satellite GHI distribution; average daily satellite direct normalized (DNI) distribution and temperature values are shown in Figures 4(a), (b), 5(a) and (b).

The average GHI reported in all stations range between 150 and 240 Wm^{-2}. This results into a corresponding global horizontal solar irradiation in the range of 3.60–5.76 kWhm^{-2} day^{-1} averaged over a 24-hour period. The northeast and west Nile sub regions in northern Uganda receive the highest GHI potential with irradiation above 4.6 kWhm^{-2} day^{-1} as shown in Figures 4(a) and (b). These are fairly flat low altitude areas as shown in Figure 7(a) and Table 3 and has experienced low cloud cover (Figure 4b). They are characterized by a GHI potential which is 26% above average. Comparison between Figures 4(a) and (b) and Figure 5(a) shows that areas with high GHI correspondingly receive higher DNI. The solar irradiation from the national DNI potential is between 3.40 and 5.75 kWhm^{-2} day^{-1} as reported by Okello et al. (2011); with northern Uganda's mean value above 4.57 kWhm^{-2} day^{-1}, in agreement with published literature. Locations close to the equator receive relatively low DNI and the average daily DNI increases with latitude. The high DNI intensities occur between 1000 hours to 1600 hours and CSPs should be designed to effectively work within this time range (Okello et al. 2011).

Results show that for the largest part of Uganda, GHI values are above 161 Wm^{-2} with solar irradiation of 3.87 $kWhm^{-2}$ day^{-1}, an amount of solar energy potential which is far higher in comparison with other parts of the world especially in Japan, Europe, and the United States where the development and deployment of solar technologies is maximum and is effectively exploited (Jain et al. 2011). In general, the average solar potential in Uganda stands at 4.6 $kWhm^{-2}$ day^{-1}. The results are in agreement with the range of GHI values in other tropical regions as published in literature.

Figure 6(a) indicates the number of daily sunshine hours. Long sunshine hours imply long periods of maximum efficiency operation for an installed solar system and therefore higher values of this indicator imply a higher solar production potential. The GHI potential for photovoltaic energy in Uganda is in the range of 1414–1902 kWh/kWc $year^{-1}$.

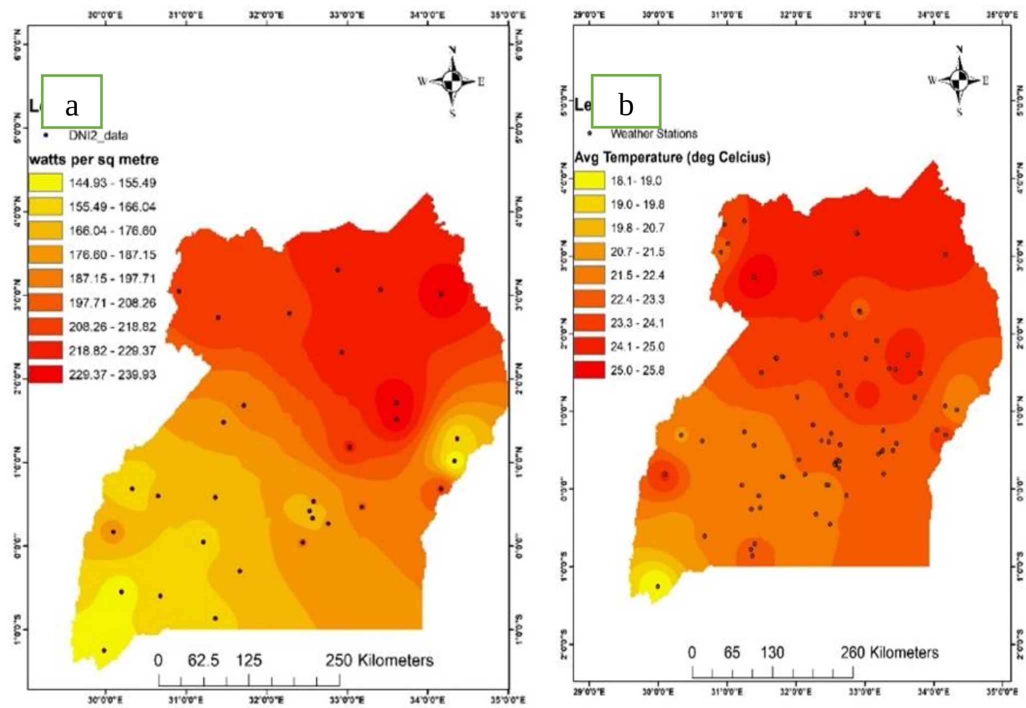

Figure 5: Map showing average daily (a) Satellite DNI distribution from January 2000 to February 2022 (b) Temperature distribution from January 2015 to February 2022.

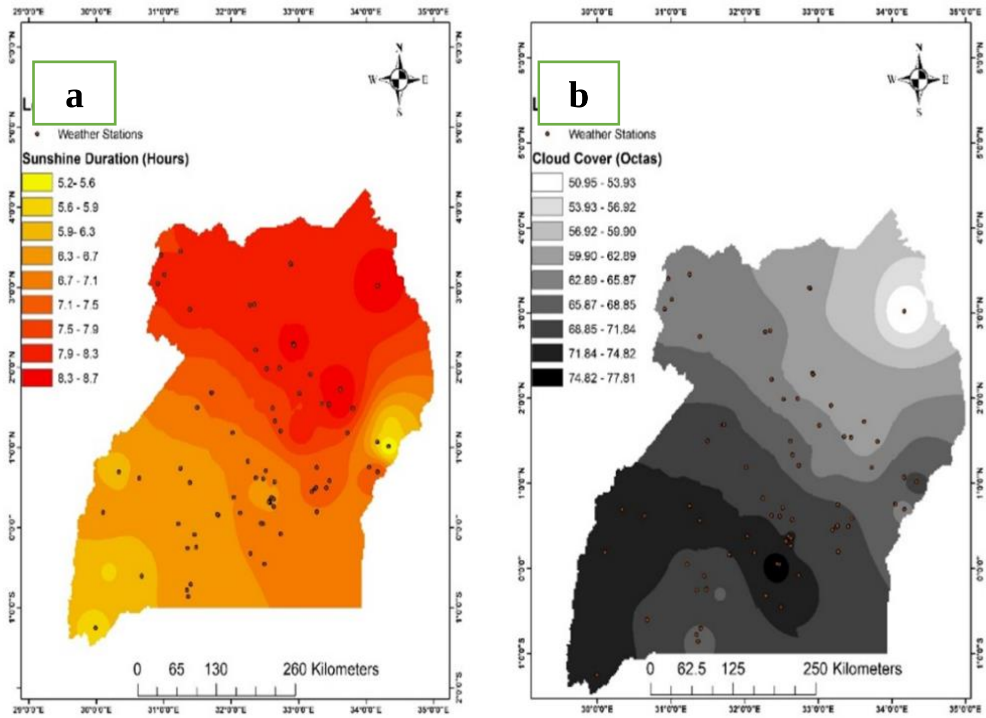

Figure 6: Map showing average daily (a) Sunshine duration (b) *Cloud Cover distribution* from January 2000 to February 2022.

Slope, accessibility and land use indicators

The spatial-temporal variability of meteorological conditions affects the solar irradiance and consequently the solar energy harvest. In addition to GHI analysis, a slope elevation map as shown in Figure 7(a) and a summary in Table 3 were developed to analyse the land relative suitability indicators. Slope and altitude are significant limitations to effective solar harvest. Usable areas should be inclined with a threshold slope of less than 4% (Gherboudj and Ghedira 2016). The hilly terrain around Mbale in the eastern Uganda, Kasese and Kisoro in southwestern Uganda do not favour large-scale solar system installations. Only 67132 km^2 of the country which is 69.3% has relief favourable for large scale solar PV power plants and CSP facilities. This area is located in the Central and Northern Uganda. The rest of the land is not suitable, mainly due to rough terrain and high slope. This is demonstrated in Map 7(a) and summarized in Table 3.

Northern Uganda (Figure 7b) has poor road network and yet the national distribution grid network follows existing road network for power distribution. More so, the settlements in Northeastern Uganda (Manyattas) are temporary with limited demands for the grid connection. Such homesteads are highly vulnerable to fire and do not favour high current electrical installations. In this case, stand-alone solar energy applications are more effective than grid connected power plants.

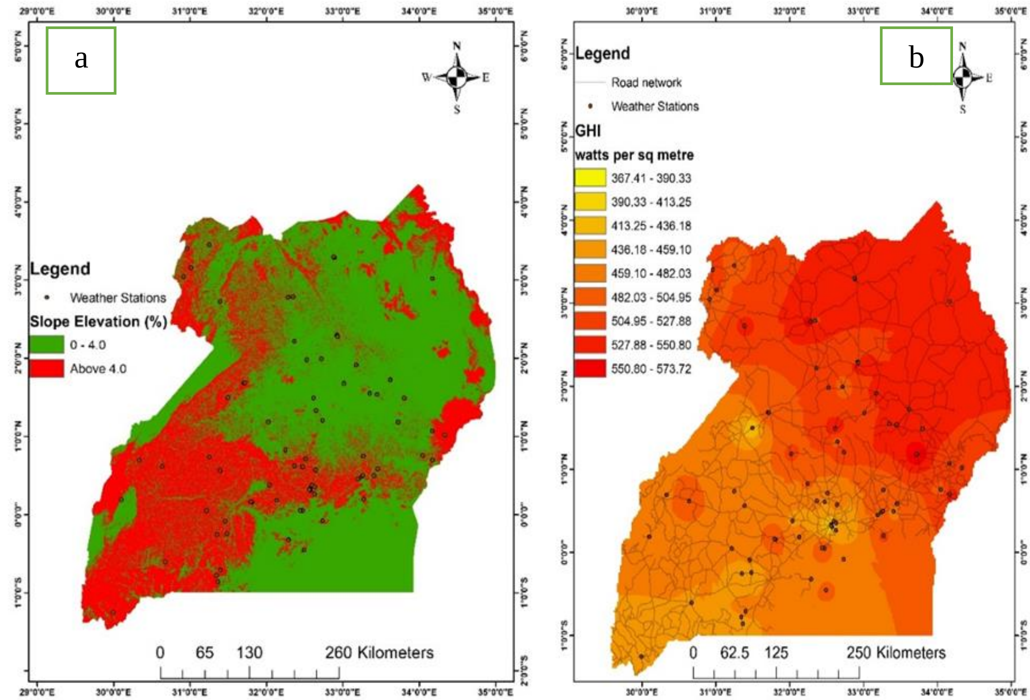

Figure 7: DEM map showing slope elevation and (b) Access to road networks map. DEM files adopted from the open source at Regional Centre for Mapping of Resources for Development RCMRD (2018).

Table 3*:* Suitable areas for large solar installation according to slope angle (%) in Uganda

S/No.	Slope (%)	Area (km^2)	Percentage (%) area
1	0 to 4	167132	69.30
2	5 to 15	55511	23.02
3	16 to 32	12150	5.04
4	33 to 53	5116	2.12
5	>54	1261	0.52

Operability indicator

This identifies areas with the average annual energy potential above the minimum threshold irradiation of 1600 kWhm^{-2} year^{-1} from GHI and 2000 kWhm^{-2} year^{-1} from DNI (Jain et al. 2011) enabling the possibility of sustainable resource exploitation. A very small area possibly on mountain peaks by this exclusion but the regions excluded due to reasons other than the DNI threshold are more significant. However, areas with high DNI potential are also possess high GHI potential as well.

Variability indicator

With an average GHI at 4.60 kWhm^{-2}, the GHI variability varies from 0.337 to 0.477 kWhm^{-2} which is 8–9% or of the average value. The monthly spatial averages vary with a relative standard deviation of less than 10% with respect to the national averages. This indicator, with regard to the solar potential reveals the PV power variability which characterizes the intermittency of the solar resource (Cavaco et al. 2016). Solar PV power plants should be built in areas with a low standard deviation of the solar potential so as to have lower energy storage requirements. This indicator allows us to evaluate the need to integrate predictive photovoltaic systems that are connected to the network. The anticipation of solar PV power production reduces electrical hazards to the network and the implementation strategy will differ depending on the standard deviation of solar potential. The higher the standard deviation, the more prediction systems will be needed to reduce this hazard.

Optimal orientation indicator

This is the ratio (AM/PM) between energy received before and after solar noon for each pixel which represents the maximum direction of solar potential according to the time of the day. This indicator evaluates the optimum angle for the orientation of solar collectors that maximizes the solar collection efficiency for fixed orientation solar systems. Table 4 shows that more than twice as much solar power is received before solar noon than after. Correspondingly, optimal solar energy exploitation favours eastern orientation as it will result into more energy collection.

Table 4: Summary of average daily AM/PM ratio in Uganda according to region

Region	Minimum	Maximum	Mean	Median	Standard deviation (%)
West Nile	2.10	2.73	2.38	2.36	8.0
Northern	2.26	2.80	2.52	2.49	7.1
Eastern	2.14	2.80	2.43	2.39	9.1
Western	2.13	3.06	2.51	2.47	11.2
Central	1.97	2.47	2.19	2.16	7.3

Conclusions

The temporal variations of diurnal average monthly daily average GHI and DNI were analysed and found to be bimodal with peaks between March and September and minimum in June–July. The average daily global horizontal solar irradiation over the country ranges from 4.16 to 5.17 kWhm^{-2} per day. The solar potential has been analysed and estimated at 1680 kWhm^{-2} year^{-1} and therefore large scale solar PV exploitation is viable for the largest part of the country. However, the land suitability shows that only 67132 km^2 of the country which is 69.3% has slope less than 4% which favours large scale solar PV power plants and CSP facilities. This is the region located in the central, eastern and northern Uganda. The hilly terrain around the Elgon Mountains in eastern Uganda, Kasese and Kisoro in southwestern Uganda do not favour large-scale solar system installations.

The inter-day solar radiation variability across the country is less than 10%, the low variability implies that large scale solar PV systems can be installed without significant storage and backup costs. The spatial-temporal indicator maps show the exploitability of the solar potential in the East African nation for PV plants, solar water heaters (GHI), or solar concentrators (DNI). The availability of this knowledge is a great contribution to the development of renewable energy in Uganda. Presence of more spatially distributed ground stations throughout the country would yield better GHI estimates. Future work should be planned to map the solar potential on the East African region or even better the entire African Continent by validating radiation estimates from weather stations scattered across Africa.

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