Spatial Mapping of Solar Potential of Ghana Using Geographic Information Systems

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Key words: Land Surface Temperature, Google Earth Engine, Global Horizontal Irradiance, Surface Albedo, solar potential, Landsat 8 OLI/TIRS.

SUMMARY

Ghana is endowed with significant amounts of renewable energy resources, that when fully exploited, can contribute to mitigating the power crisis facing the country as well as reducing the rates of forest depletion and CO2 emissions. Even though solar energy potential in Ghana is estimated at 35 EJ, its exploitation is low. (Mensah et al., 2017) For the utilization of a solar energy potential and system, knowledge about the solar irradiation potential in every location is required. In addition, a solar energy map is practicable for further evaluation of the renewable energy option and strategic planning, such as for site location (Joshi, 2013). This research therefore, aimed at developing solar energy potential map for the exploitation of solar energy to support other power sources to meet the growing demand of electricity in Ghana. The solar potential map was developed using Google Earth Engine (GEE). The Landsat 8 OLI/TIRS satellite data was used to generate the Global Horizontal Irradiance (GHI) over the various regions. The Dark Object Subtraction method was used in computing the solar radiation from Landsat 8 and had a minimum and maximum of about 1.5 kWh/m^2 and 7 kWh/m^2 respectively from 2014 to 2018. A Time series analysis was performed on the solar radiation monthly data for each year from 2014 to 2018. This was to find out the trend of increase and decrease in solar radiation over the months in the various years. The Surface Albedo was also calculated for the regions to know the general reflectivity of solar radiations over the areas. The mean of the solar radiation was computed from 2014 to 2018 as well as that of the Land Surface Temperature (LST) and Surface Albedo. The derived solar potential showed that the upper part of Ghana had a higher potential for solar radiation than that of the lower regions. The Northern Region had a very high solar potential, followed by the Upper East and Upper West Region. Volta Region showed a fairly minimum solar potential values.

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INTRODUCTION

Demand for electricity in Ghana over last two decades has been growing by 10-15 percent yearly. The main drivers of electricity demand include the growing viable manufacturing sector and increasing populace. Present electricity forecast estimates increase in usage of electricity to at least 7% each year.

Inadequate and unreliable provision of electricity is a major constraint to the economic growth of Ghana (Africa and Support, 2016). “Hydropower has been the major energy resource for electricity generation to meet power needs of Ghanaians in past decades. However, as electricity demand increases more than supply, various thermal generation plants as well as renewable sources (especially solar energy) have been recently integrated into the national grid to meet these demands. Renewable energy resource is a major solution to the energy needs of trade and industry sectors of Ghana (Mensah et al., 2017)

Ghana has abundant renewable energy resources that can contribute to continuous profitable growth of the country. Clean and inexpensive power for heating, cooking and empowering enterprises for improved manufacturing can be provided through small-scale solar energy systems. The exploitation of solar energy for efficient power generation has necessitated Ghana’s Parliament to pass Renewable Energy Act in 2011. This is to make sure that renewable energy is fully exploited for the provision of clean and inexpensive alternative energy to it citizenry.

Ghana waved import duty on renewable energy equipment and machinery to encourage private sector venture in renewable energy, especially solar energy (IRENA, 2015). According to Mensah et al., (2017), 35 EJ is the estimation of Solar energy potential in Ghana. However, effective solar energy exploration and utilization requires understanding of solar radiation potential in all locality (Joshi, 2013).

Even though, “Ghana has embarked on a 155-MW solar plant project to augment electricity generation capacity of the nation by 6 % and also meet about 20% of the National renewable energy goal of 10% electricity generation by 2020” (Mensah, Boahen and Amoabeng, 2017), there is the need for developing solar potential map to additionally evaluate solar energy decision and planning, such as location analysis (Joshi, 2013). Ghana needs a detailed solar energy potential map covering the entire country and this can be developed using GIS to ensure development of solar potential contribute to electricity generation needs.

Geographic Information System (GIS) is suitable tool to evaluate prospective sites for solar energy development and proximity analysis (Joshi, 2013). Such a useful resource map would enable Ghana to take advantage of this free and available renewable energy. The aim is to develop solar potential map for exploitation of solar energy to support other power sources to meet the growing demand of electricity.

1.1 Research Problem

Whereas the demand for electricity in Ghana over the last two decades has been increasing due to growing Commercial/Industrial sectors and high population growth, the cost of generation and subsequently offer to consumers has led to situations where there are production shortfalls or labour agitation for cost of accessibility.

Hydropower has been the major energy resource for electricity generation over the last two decades but as the demand increases more than the current hydro generation capacity; various mixes of thermal generation as well as renewable sources (especially solar energy) have been recently integrated.

The percentage inclusion of thermal at 63.9% has led to higher tariffs whereas Ghana is highly endowed with natural renewable energy potential sources. For instance solar potential in Ghana alone is estimated at 35 EJ (Mensah et al., 2017).

Notwithstanding the various works done on Solar and Wind Potential Asumadu-Sarkodie et al., (2016); Mensah et al., (2017), not much has been done to develop solar energy potential maps for further evaluation and exploitation of the renewable energy option and planning, sites for solar farms. This research seeks to fill this void by providing a detailed solar energy potential map covering the entire country using GIS.

1.2 Aim and Objectives

1.2.1 Aim

To develop solar energy potential map for exploitation of solar energy to support other power sources to meet the growing demand of electricity.

1.2.2 Objectives

- To identify areas with high Global Horizontal Irradiance (GHI) of the regions for five years.
- To model the identified areas with high GHI of the various regions throughout the year.
- To create thematic solar irradiation maps for the various regions

1.3 Research Questions

- Which regions have high Global Horizontal Irradiance (GHI) for particular years?
- How would a solar potential map be prepared for Ghana?
- How effective and efficient are these thematic maps for decision making?

MATERIALS AND METHODS

1.4 Study Area

The study covers the entire regions of Ghana (Figure 3.1). Ghana, officially the Republic of Ghana, is a country located along the Gulf of Guinea and Atlantic Ocean, in the sub region of West Africa. Spanning a land mass of 238,535 km^2 (92,099 sq mi), Ghana is bordered by the Ivory Coast to the west, Burkina Faso to the north, Togo to the east and the Gulf of Guinea and Atlantic Ocean in the south. Its centroid is indicated as 7° 49′ 0″ N, 1° 3′ 0″ W (DMS) or 7.816667, -1.05 (Decimal) or 30N 715024 864528 (UTM).

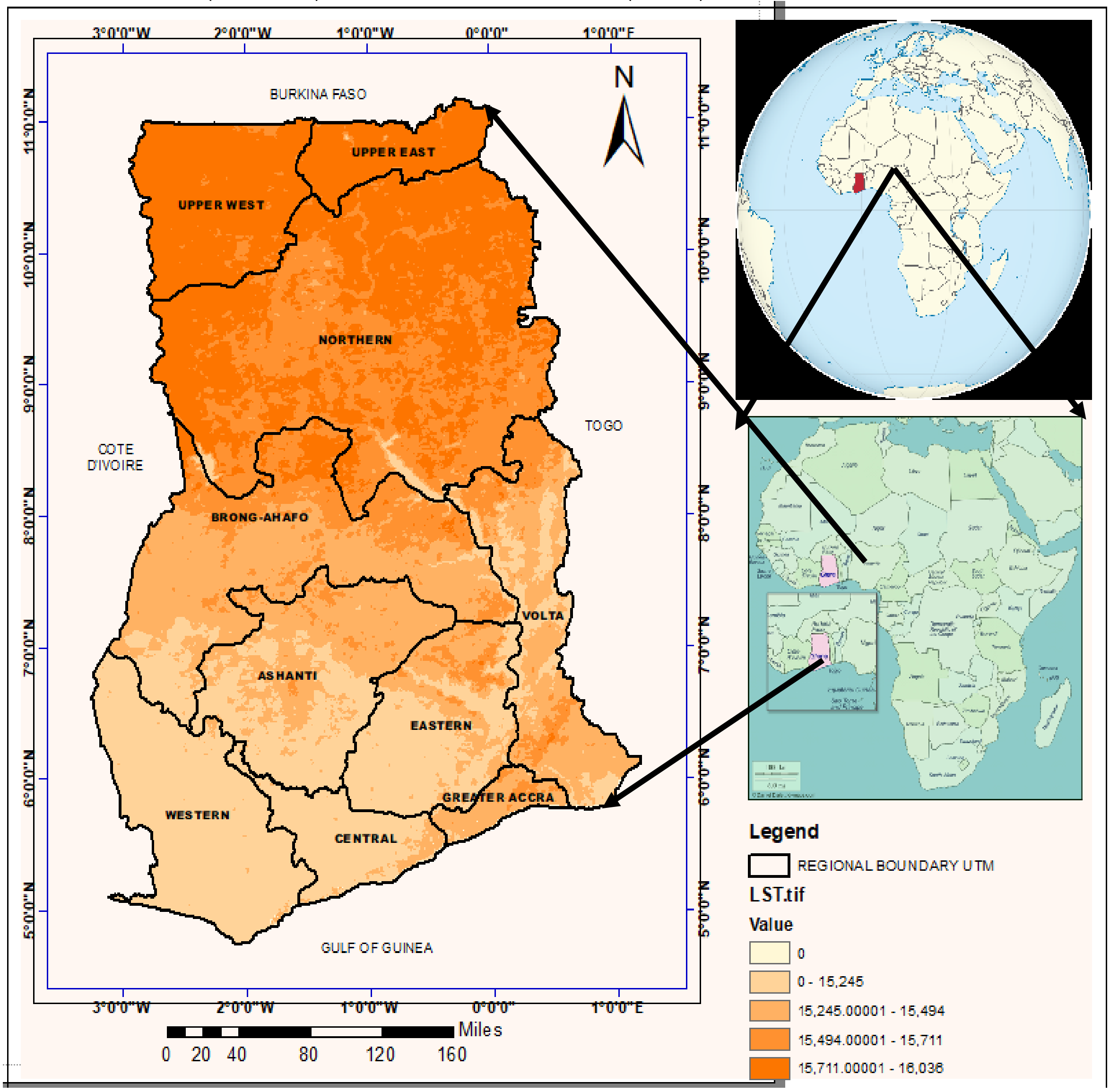


Figure 3.1 Study Area (Map of Ghana)

1.5 Materials Description

1.5.1 Satellite Data

Multispectral satellite images Landsat 8 OLI/TIRS from 2013-2019 at different spectrums are essential for the calculation of the indexes, Solar Radiation, Land Surface Temperature and Albedo. These datasets were derived from existing Google Earth Engine image collections of U.S. Geological Survey Earth Resources Observation and Science Center (EROS) that are constantly updated (**Table 3.1**).

Table 3.1 Landsat 8 OLI/TIRS Dataset Description

Satellite and dataset used for the geospatial analysis					
Data	Variables	Spatial Resolution	Temporal resolution	Duration	References
Landsat -8	LST, Albedo, Solar Radiation	30m	16days	2013-present	NASA/USGS

Table 3.2 List of instruments used for the field verification

Instrument	Purpose of usage
Pyrheliometer	Measurement of Direct Normal Irradiance (DNI)
Pyranometer	Measurement of Global Horizontal Irradiance (GHI)

Table 3.3 List of software used in this study

Software	Purpose of usage
Google Earth Engine	Coding, Image Processing, Time series and analysis
ArcGIS Desktop	GIS analysis and Mapping
Microsoft Suite	Structuring, Compilation and editing

The sequence and method used in embarking on the research are indicated in the flowchart shown in Figure 3.2

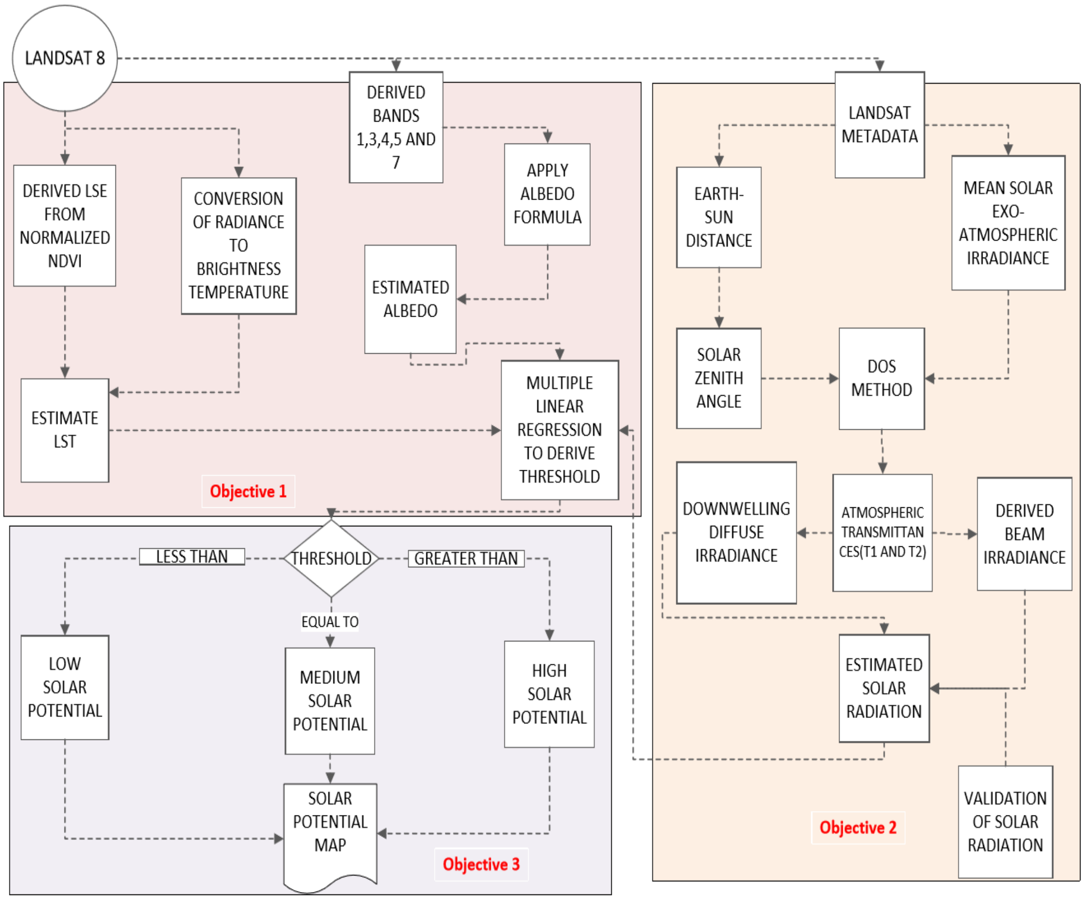


Figure 3.2 Methodology Flowchart

1.6 Land Surface Temperature (LST)

The land surface temperature was derived by using the surface reflectance image collection and the Landsat image collection of Landsat 8. Normalized Difference Vegetation Index (NDVI), Surface reflectance and the Top of Atmosphere Radiance (TOA_rad) was used in deriving the LST (Jeevalakshmi, Narayana Reddy and Manikiam, 2017) (figure 3.3).

Brightness temperature (BT) was derived from the surface reflectance image collection. Brightness Temperature (BT) for Landsat 8 was derived using band 10 from the surface reflectance image collection.

Normalized Difference Vegetation Index is calculated using Landsat 8 at 30-meter resolution. The bands used for the calculation of NDVI were Bands 5 and 4.

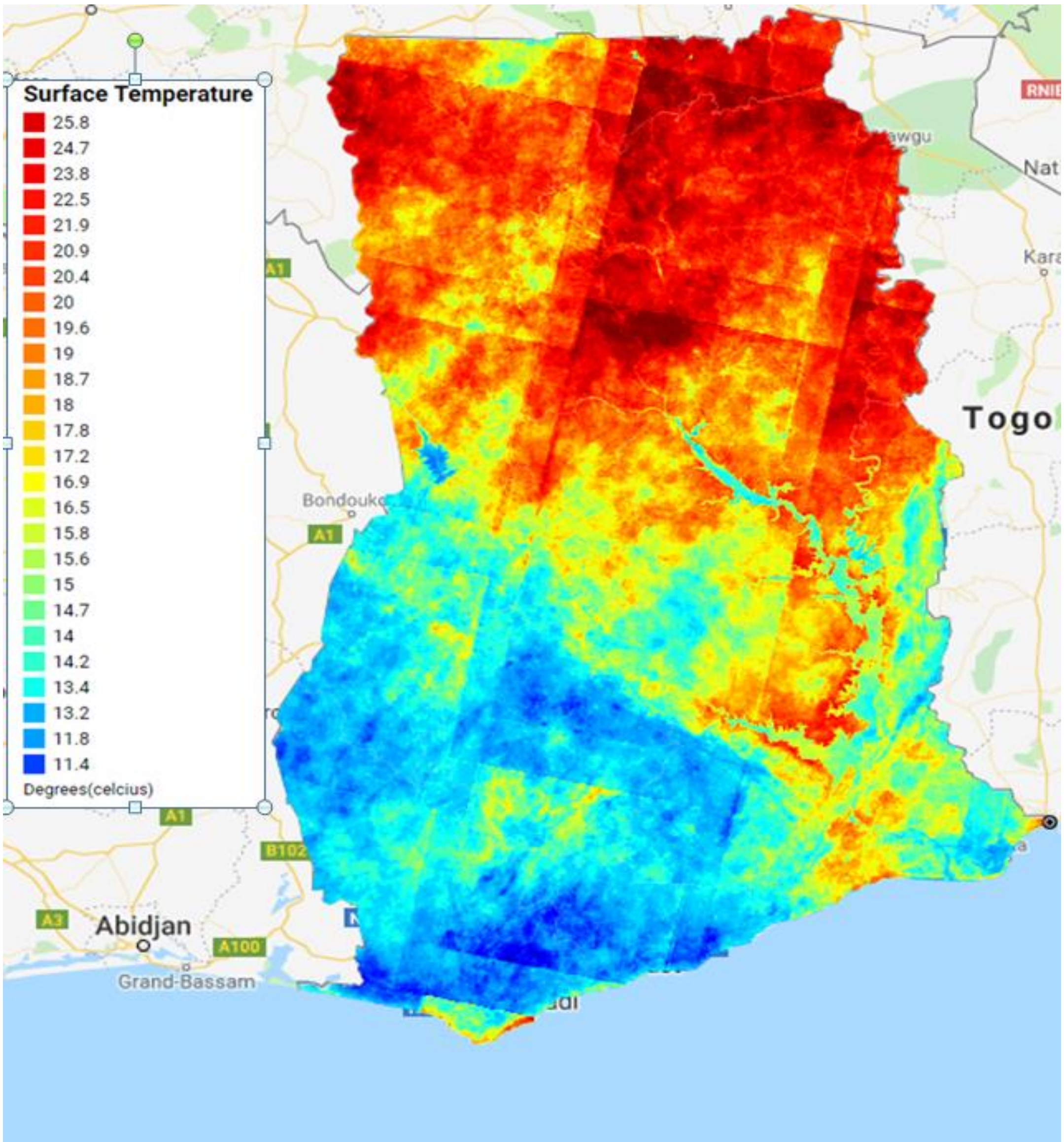


Figure 3.3 Land Surface Temperatures (LST)

1.7 Albedo

The estimation of Albedo was computed in Earth Engine using Landsat 8 satellite data. The Landsat 8 image was converted from digital numbers to Top of Atmosphere (TOA) reflectance which has already been corrected in the image collection found in Google earth engine. The formula for calculating the albedo from Landsat, developed by Liang *et al.*, (2003) and normalized by Smith, (2010) is presented in equation 10 (Yale, 2010).

$$a = \frac{((0.356 * B1) + (0.130 * B2) + (0.373 * B3) + (0.085 * B4) + (0.072 * B5) - 0.018)}{1.016} \quad [10]$$

where B1, B2, B3, B4, and B5 are Landsat bands 1,2,3,4 and 5. Figure 3.4 shows obtained surface albedo distribution.

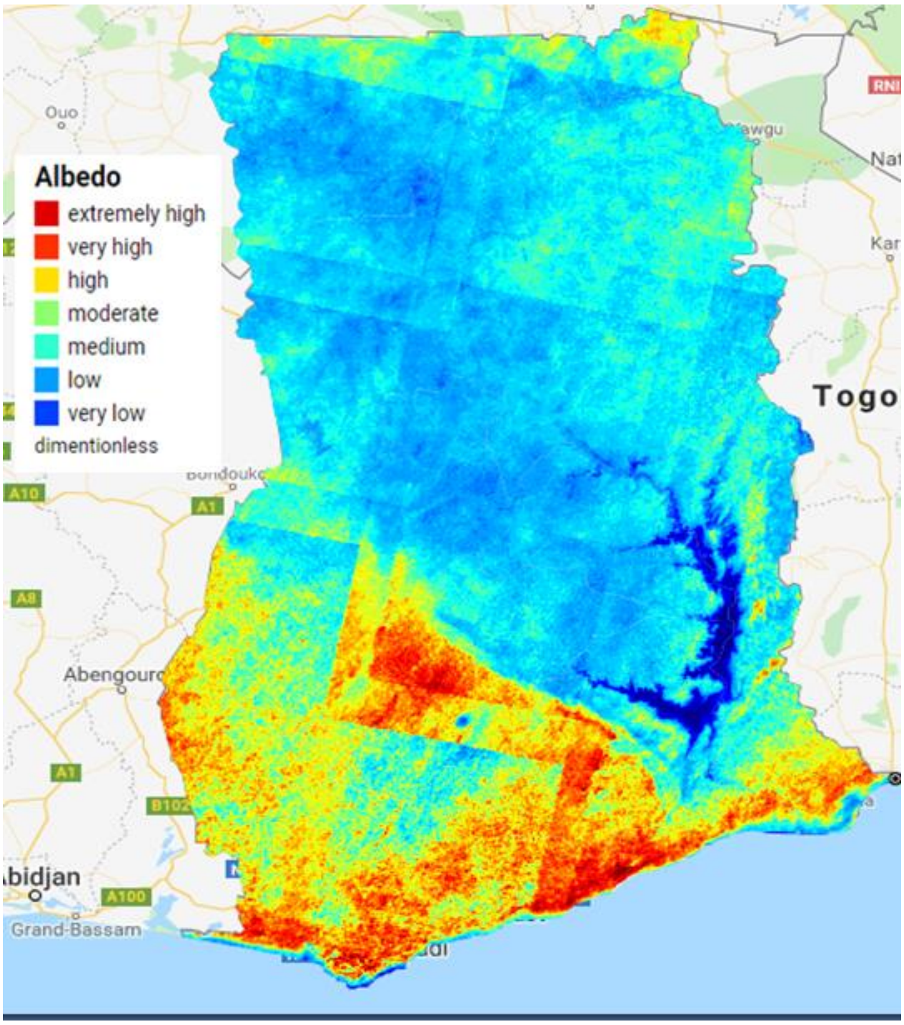


Figure 3.4 Surface Albedo

1.8 Solar Radiation

The general formula for surface solar radiation is given by the sum $G=I_d + D$, where I_d is the beam irradiance and D is the diffuse irradiance.
From the equation for Land Surface Reflectance (ρ) which is the ratio of reflected versus total power energy, expressed as the formula:

$$\rho = \left(\frac{\pi\left(L_{sat} - L_p\right)d^2}{(T_{\uparrow}(E_0 \cos\theta_z \, T_{\downarrow} + E_{\downarrow}} \right) \quad [11]$$

Where d is the earth-sun distance in astronomical units ; Eo the mean solar exo-atmospheric irradiances ; T↓ the atmospheric transmittance in the viewing direction ; T↑ the atmospheric transmittance in the illumination direction and θz the solar zenith angle in degrees, which is equal to θz = 90° - θe where θe is the sun elevation (BENHARRATS *et al.*, 2017).

The equation (11) shows the relationship between the land surface reflectance ρ, the spectral radiance at the sensor's aperture L and the incoming irradiance at the earth surface G. The global irradiance can then be deduced from the denominator of this formula. This irradiance expression is similar to the general formula of surface solar radiation (Mesri-Merad, 2012) given by the sum G = I_d + D, where I_d is the beam irradiance and D is the diffuse irradiance. The Landsat global irradiance is deduced as follows (Equation 12):

$$G = E_0 \cos\theta_z T_\downarrow + E_\downarrow \qquad [12]$$

Where $G = E_0 \cos\theta_z T_\downarrow + E_\downarrow$ is the beam irradiance and D = E↓ is the downwelling diffuse irradiance.

The Dark Object Subtraction (DOS) method of atmospheric correction was used to derive the transmittances T↓, T↑, and the downwelling diffuse irradiance E↓ (mujtaba, 2007). The DOS assumption is that radiances of fully shaded pixels received at the satellite are due to the atmospheric scattering (path radiance) and the fact that very few targets on the earth's surface are absolute black grant to assume 1% minimum surface reflectance for the dark objects. The path radiance is calculated as (Equation 13)

$$L_p = M_L DN_{min} + A_L - \frac{0.01(E_0 \cos\theta_z T_\downarrow + E_\downarrow)T_\uparrow}{\pi d^2} \qquad [13]$$

where M_L is the band-specific multiplicative rescaling factor and A_L the band-specific additive rescaling factor from landsat metadata. The minimum DN value, DNmin, was selected as the darkest DN.

$E_\downarrow$ is obtained by πd^2 and the estimation of T↓ and T↑ is done iteratively. From the DOS1 T↓=T↑=1.o which enables one to determine Γ, where Γ is the optical thickness for Rayleigh scattering. This enabled the determination of Tdown in equation 14:

$$T\downarrow = e^{-\tau/\cos\theta_z} = 1 - \frac{4\pi L_p}{E_0 \cos\theta_z} \qquad [14]$$

Figure 3.5 shows the distribution of solar radiation across the country.

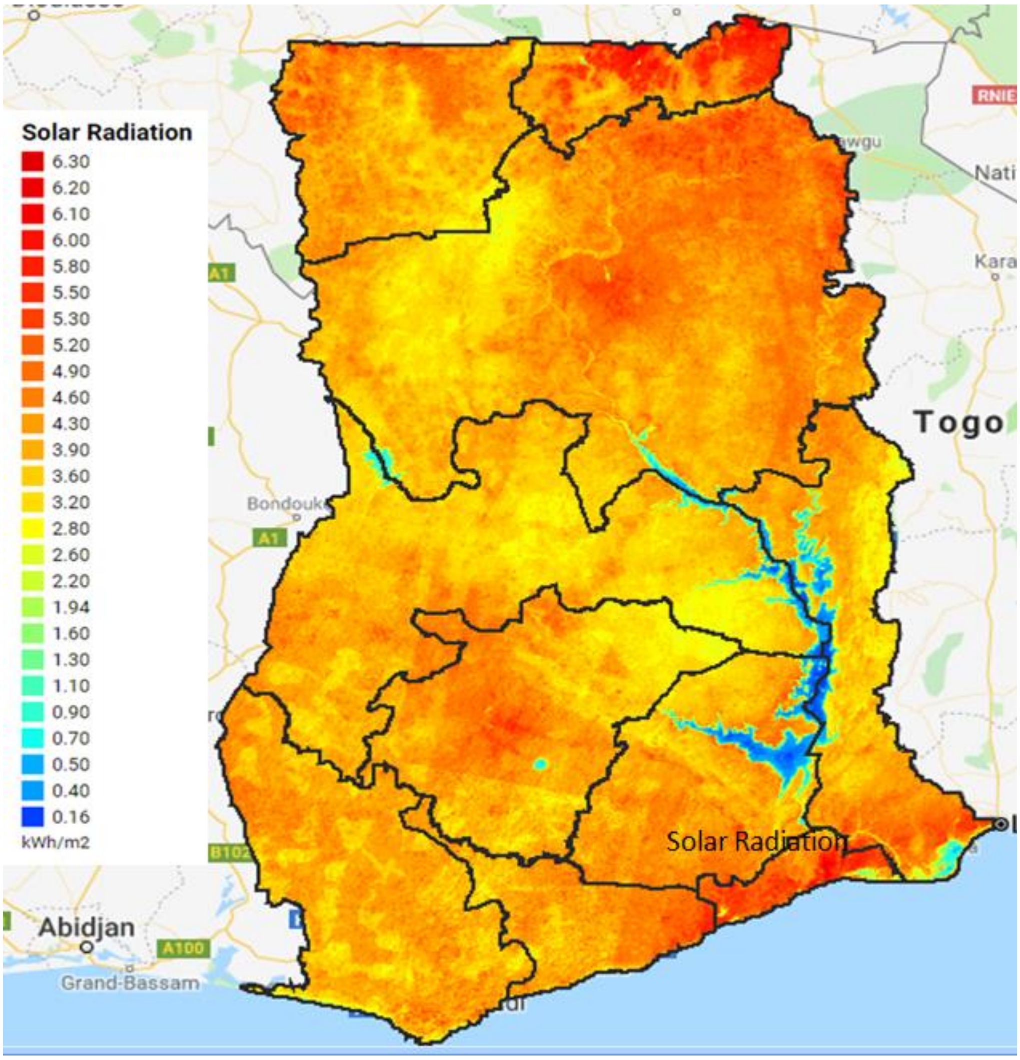


Figure 3.5 Solar Radiation

1.9 Validation of Solar Radiation

Validation of the computed solar radiation image was done by using the long-term yearly average of global horizontal irradiation of Ghana from the World Bank Group ("Global Solar Atlas," n.d.) (https://globalsolaratlas.info). The resolution of the GHI from the World Bank was 1 kilometre. The calculated solar radiation with the resolution of 30 metre was resampled to the resolution of 1 kilometre. A linear fit model from earth engine algorithms was applied to the computed solar radiation and the GHI from the World Bank group. The result was the offset which is the intercept and the scale which refers to the slope of the line. The result shows which area is of increasing trend and decreasing trend.

1.10 Developing Solar Potential Map

To develop the solar potential map, the two calculated parameters, Land Surface Temperature (LST) and Albedo were used. The solar radiation data was regressed with both LST and Albedo to find the correlation betwwen LST and the Albedo data. Linear Regression was used in this process to deduce how much the independent variables, LST and Albedo correlate with the Solar radiation data. The Google Earth Engine was used to compute the LST and Albedo and the linear regression.

An equation was deduced to compute the intensity of solar radiation from 2014 to 2018 using the pixels of the image to produce the solar potential map. The equation states that if the pixel value of solar radiation is greater than the mean solar radiation, and the albedo pixel values is also greater than the mean albedo, and the LST pixel values are also greater than the mean LST, then assign a value of one (1) indicating higher solar potential. Pixel values of solar radiation, albedo and LST, equal to their respective mean are assigned a value of zero (0) indicating medium solar potential. While, pixel values of solar radiation, albedo and LST, less than their respective mean, are assigned a value of negative one (-1) indicating low solar potential. The results were used to produce the solar potential maps showing areas of high, medium and low solar potential (Figure 4.4).

RESULTS AND DISCUSSIONS

1.11 Estimation of Solar Irradiance

The mean of the solar radiation was computed from 2014 to 2018 as well as that of the LST and albedo. The result of the computation was a coefficient of LST and Albedo. The coefficient tells how much the dependent variable which is Solar Radiation is expected to increase when that independent variable increases by one (both LST and Albedo), holding all the other independent variables constant. The Linear regression had a residual of 49.4. As seen in Figure 4.1, the distribution of LST coefficient is seen to have more positive values than negative values with a peak of about 10,000 pixels ranging from 0.002 to 0.006. Negative values represent pixels that have negative relationship with the dependent variable, that is, Solar Radiation. Positive values represent pixels that have positive relationship with the dependent variable, that is, Solar Radiation. From the histogram distribution, more pixel values had values ranging from 0.002 to 0.010 while few pixels had values ranging from 0.000 towards the negatives. This may be due to other factors that affect surface temperature such as vegetation, human activities and others. This shows that when Solar Radiation increases temperature also increases.

From Figure 4.2, the histogram of albedo showed no negative values, which indicate that the albedo had a very good correlation with solar radiation. In the Distribution, more pixel values ranged from 0.000022 to 0.000032 which shows that when solar radiation increases, the albedo also increases positively.

The Figure 4.3 shows the histogram distribution of solar radiation. The mean of the solar radiation was computed as 4.613 kWh/m^2 which was used as a threshold value. Again the mean of the albedo and Land surface temperature were computed and found to be 13852.5178 and 18.27 degrees respectively. These three thresholds were used to compute the solar potential over the various regions as shown in Figure 4.4.

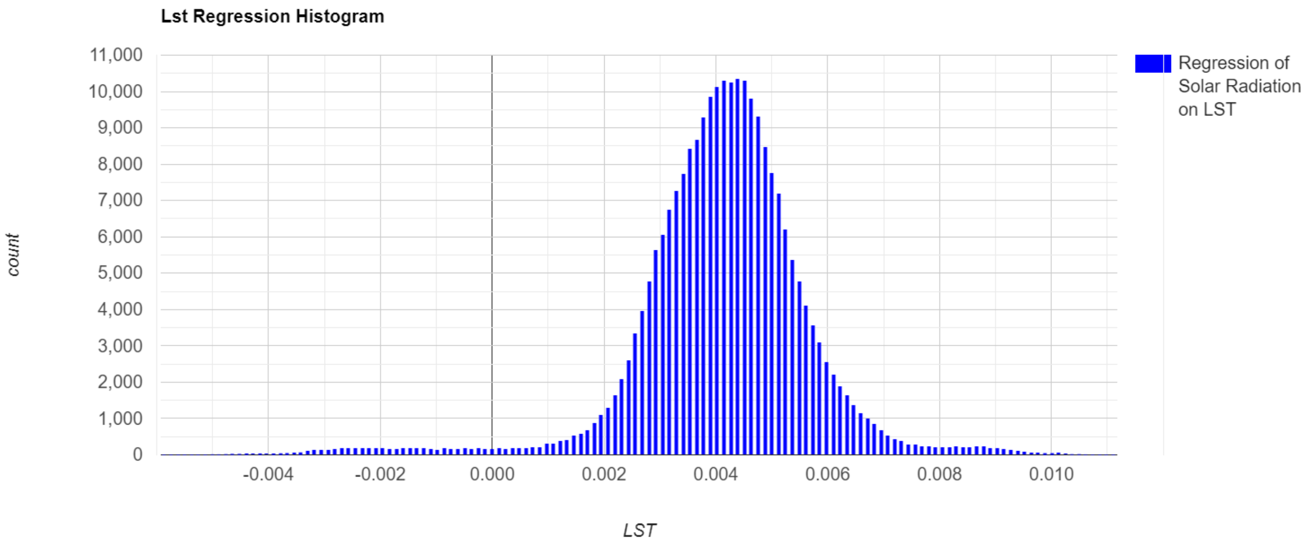


Figure 4.1 LST Regression Histogram

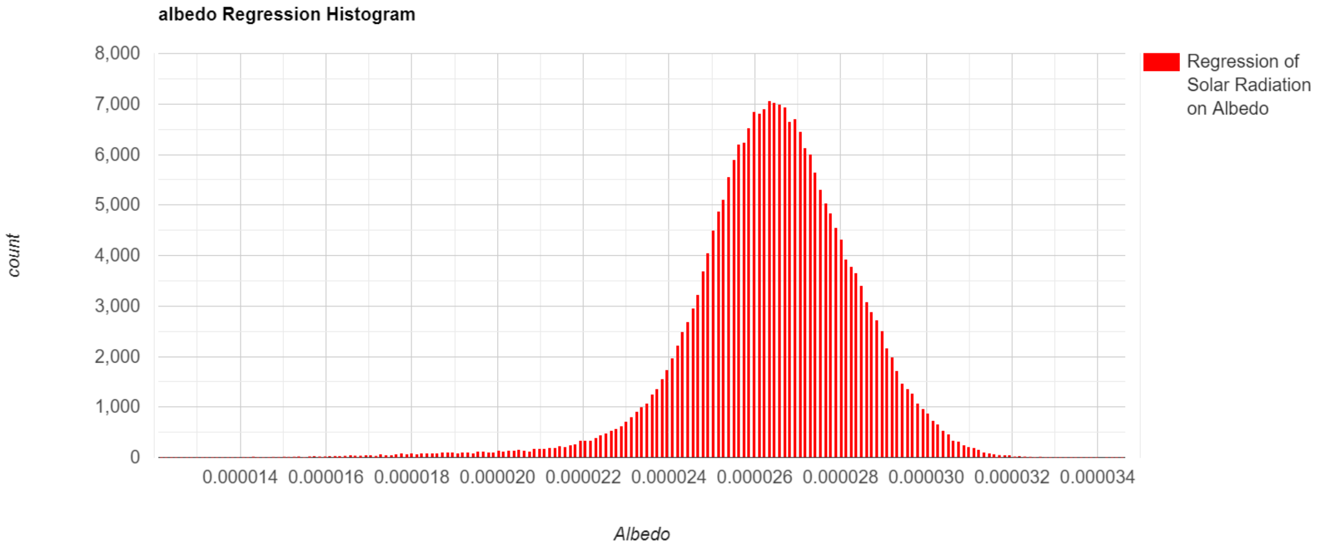


Figure 4.2 Albedo Regression Histogram

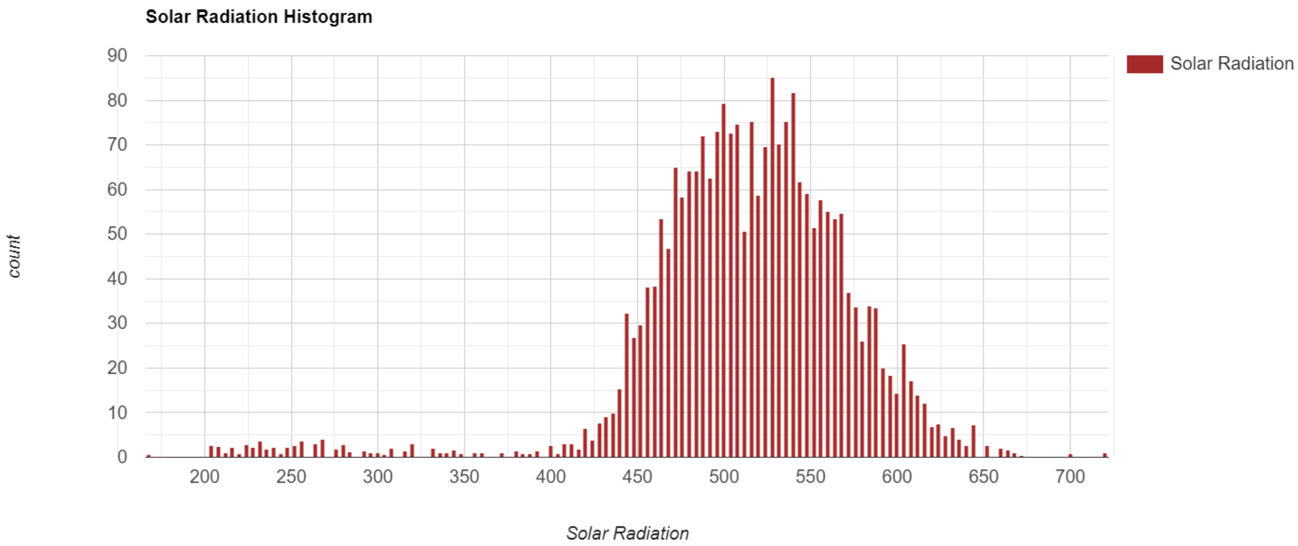


Figure 4.3 Solar Radiation Regression Histogram

Figure 4.4 shows the solar potential across the country.

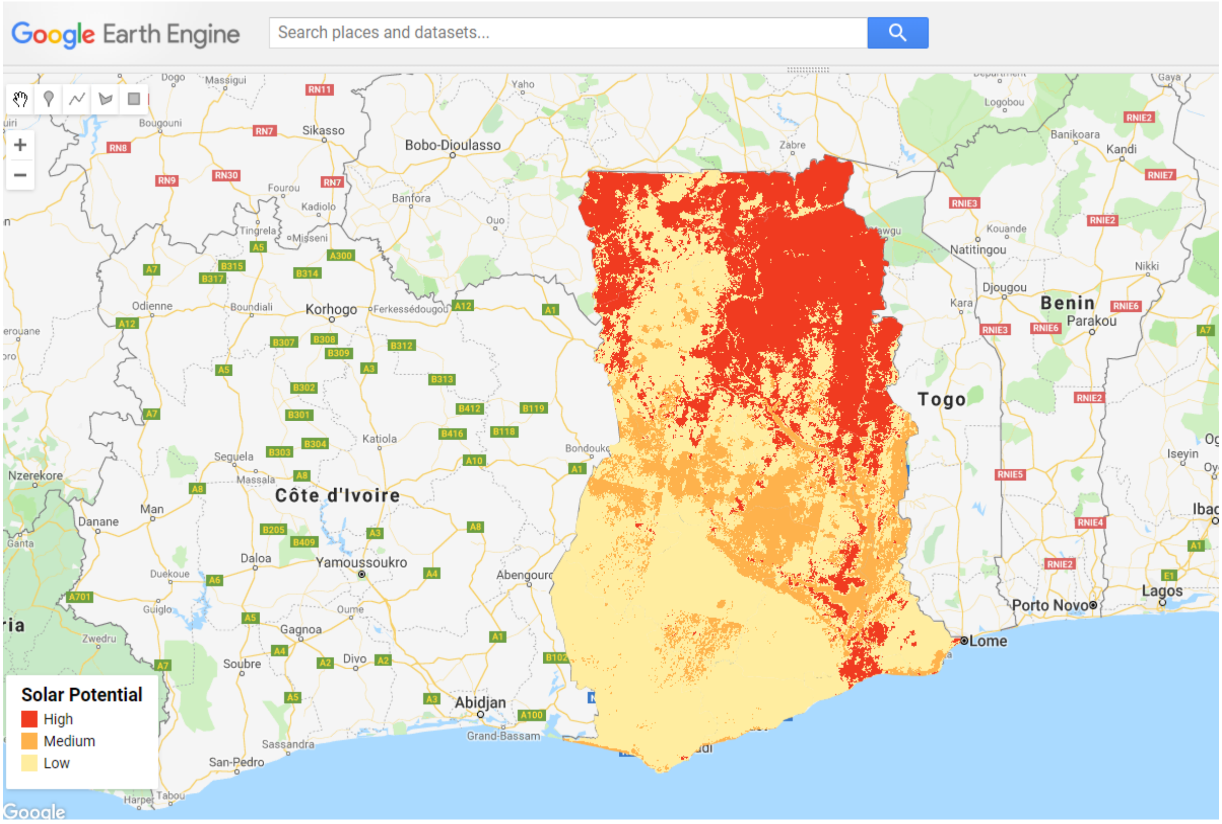


Figure 4.4 Estimation of Solar Potential

1.12 Monthly Solar Radiation across the Regions

The Time series analysis performed on the solar radiation monthly data for each year from 2014 to 2018 was to find out the trend of increase and decrease in solar radiation over the months in the various years. The year 2014 had a peak of 0.785 kWh/m^2 in August slowly declining to 0.358 kWh/m^2 in December as shown in Figure 4.5. The year 2015 also had a peak of 0.828 kWh/m^2 in the month of October and declined drastically in the month of December to 0.243 kWh/m^2 (Figure 4.6). Finally, the year 2018 had an early peak of solar radiation in the month of March at 0.98 and had its decline towards December at 0.32 kWh/m^2 (Figure 4.9).

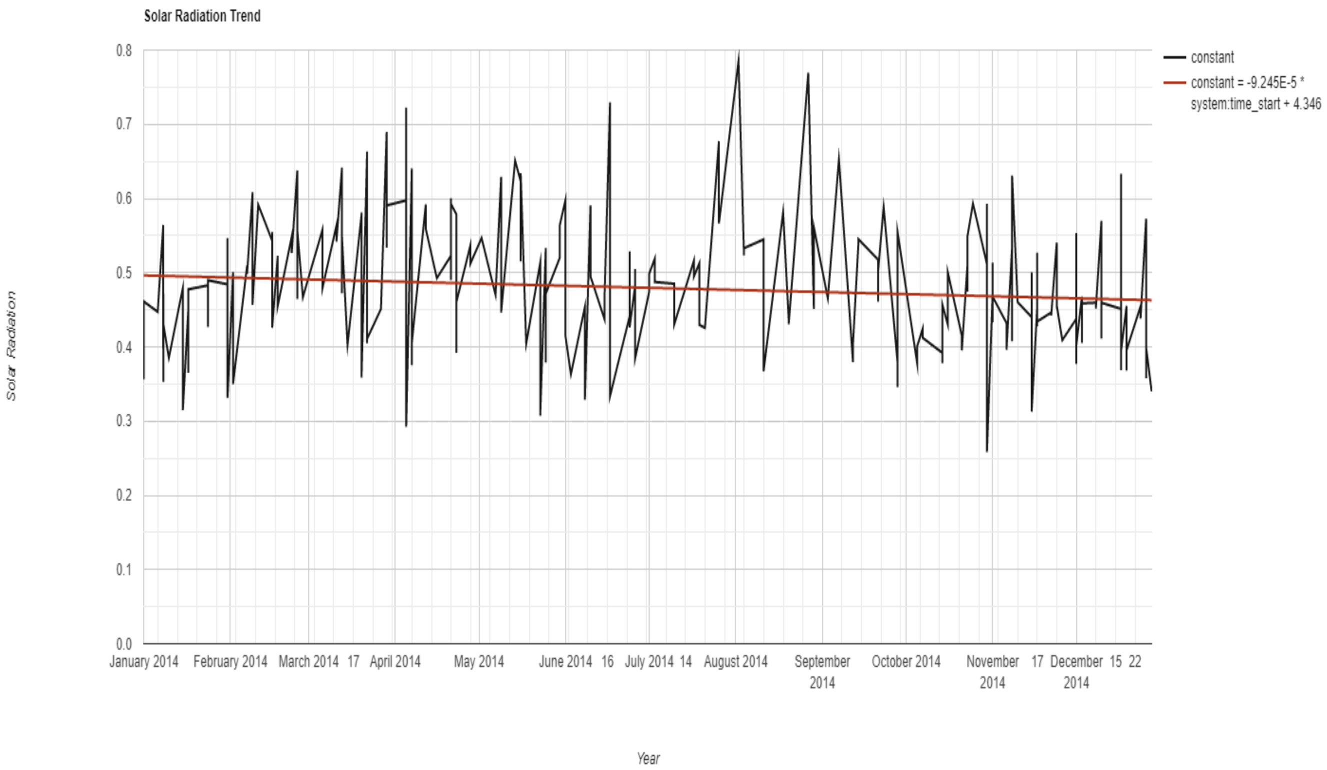


Figure 4.5 Time series of solar radiation in 2014

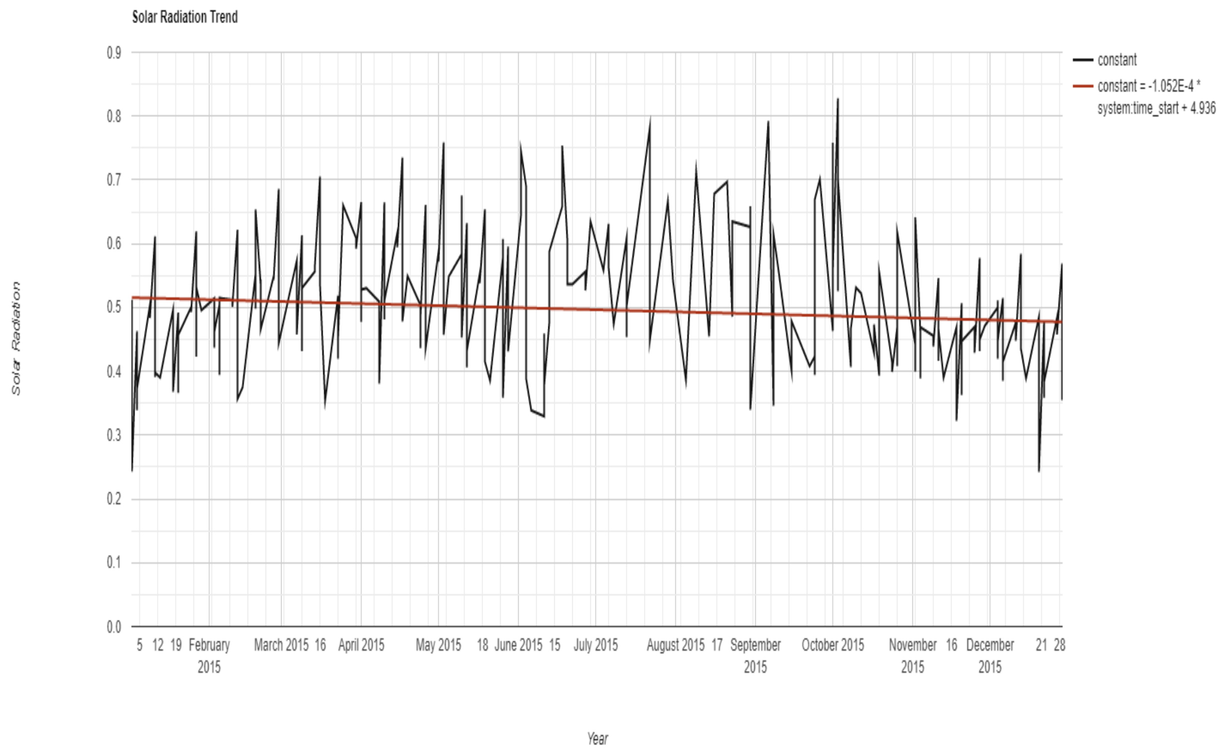


Figure 4.6 Time series of solar radiation in 2015

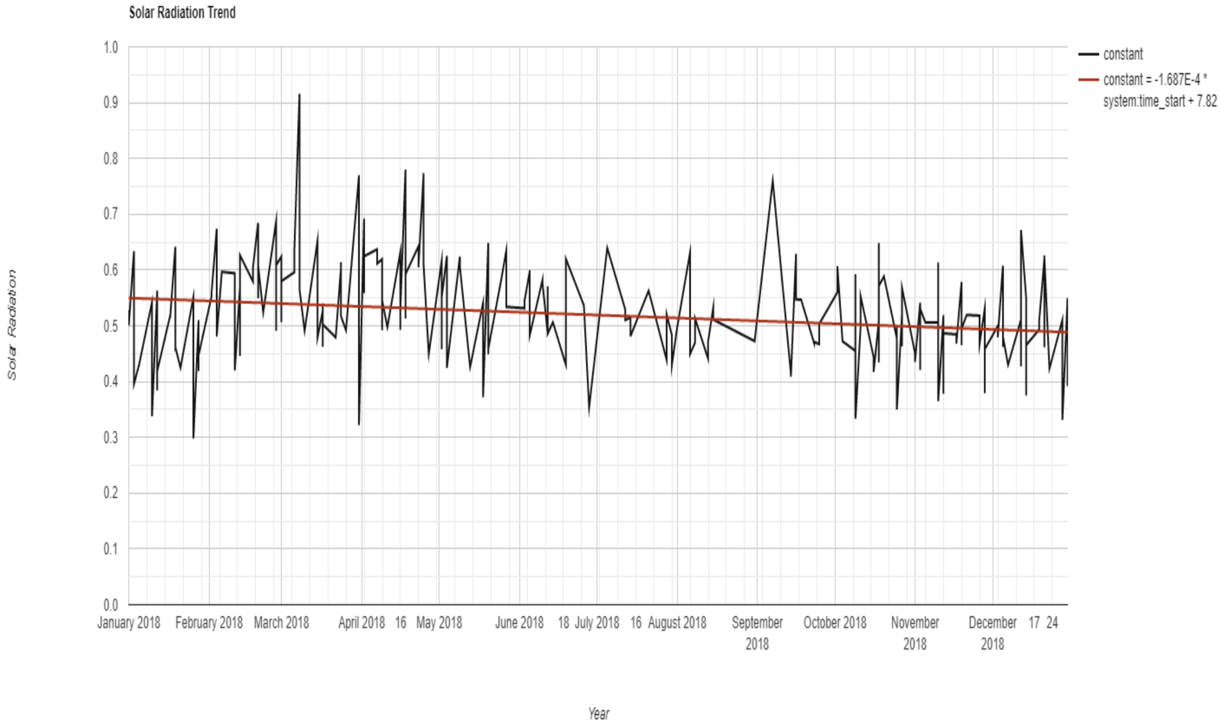


Figure 4.9 Time series of solar radiation in 2018

The Dark Object Subtraction method used in computing the solar radiation from Landsat 8 had a minimum and maximum of about 1.5 kWh/m^2 and 7 kWh/m^2 respectively from 2014 to 2018. Comparing it to the GHI from the World Bank Group global solar atlas computed as of 2017, which had a minimum and maximum 4.45 kWh/m^2 and 5.969 kWh/m^2. it could be said that they are almost identical and the marginal difference may be from the time frame of deriving the GHI values. In the findings, a linear regression was computed over the solar radiation and the GHI derived from the World Bank Group and the residual was found to be 0.56. The Limitations to this method of estimating the global Solar Irradiance is that the ground truth data obtained from the Ghana Meteorological Department for validation were recordings in minutes as pdf document which could not be used because the project data were raster data.

1.13 Solar Potential of the various Regions

The derived solar potential showed that the upper part of Ghana had a higher potential for solar radiation than that of the lower regions as shown in Figure 4.11. Among the regions with higher solar potential are the Upper East Region, Upper West Region, Northern Region and the Volta Region. The higher solar radiations that incident on the surface of the earth might contribute significantly in the potential value of the regions. As seen in Figure 4.11, The Upper East had a very high solar potential, followed by the Upper West Regions Region.

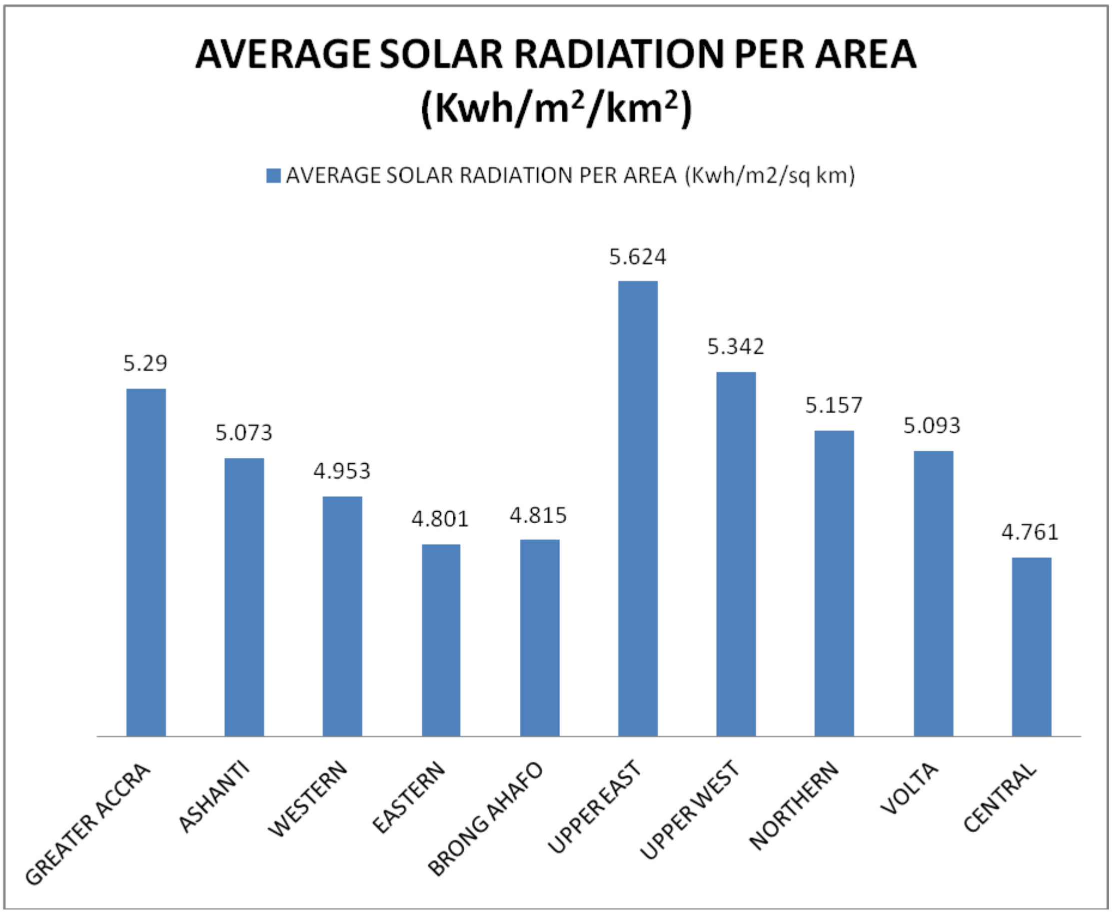


Figure 4.11 Bar chart showing solar potential over the various regions

The solar potential map was developed for all the Ten (10) regions as shown in figure 4.12 and 4.13.

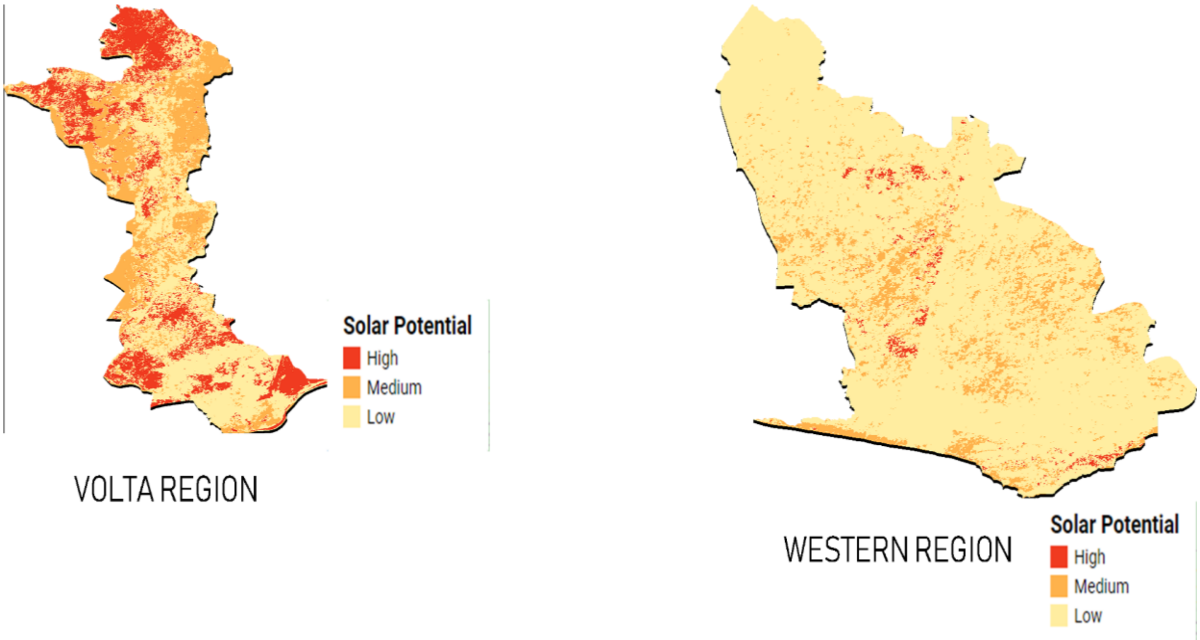
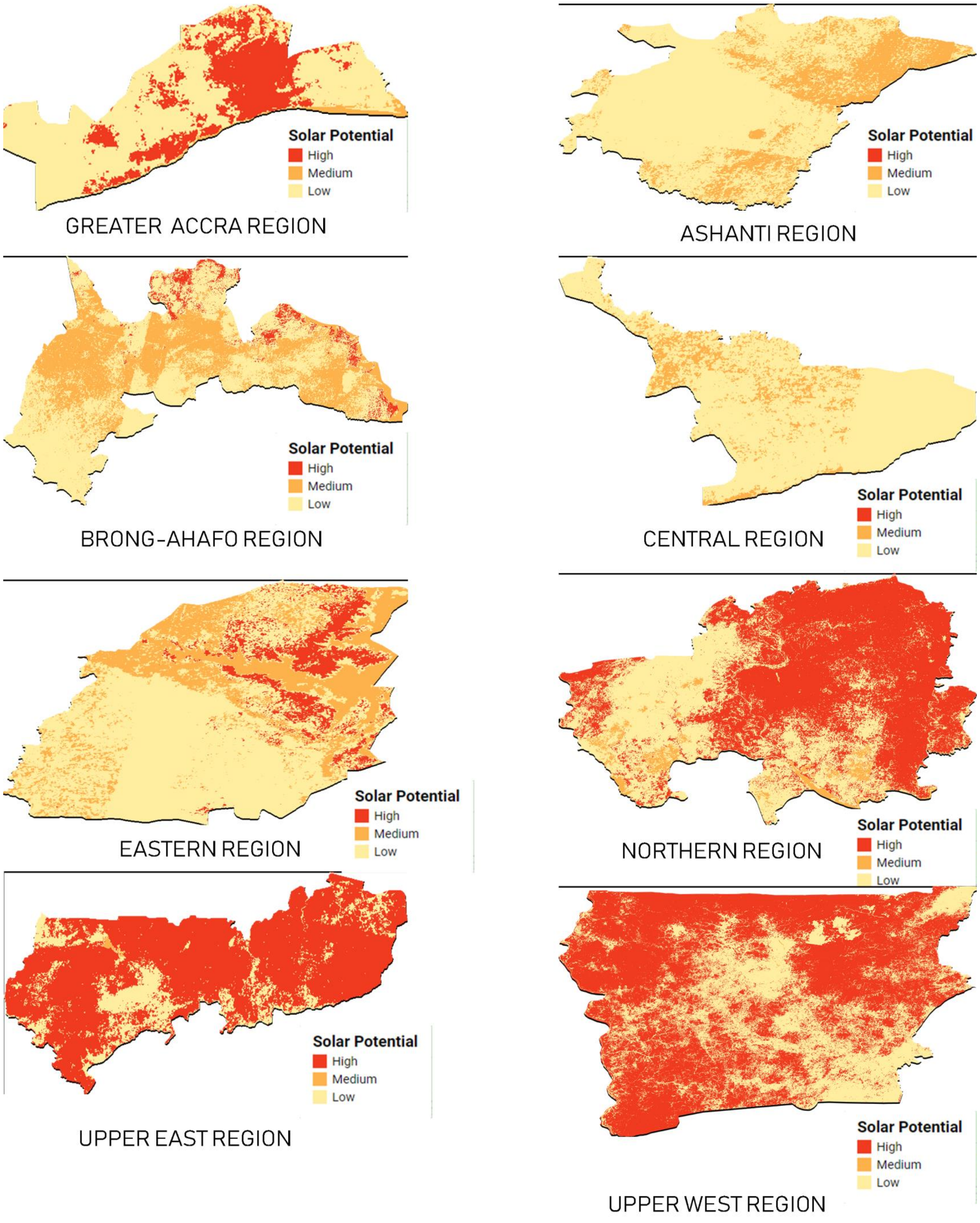


Figure 4.12 Solar Potential Maps of the various Regions of Ghana


Solar Potential
High
Medium
Low
GREATER ACCRA REGION
Solar Potential
High
Medium
Low
ASHANTI REGION
Solar Potential
High
Medium
Low
BRONG-AHAFO REGION
Solar Potential
High
Medium
Low
CENTRAL REGION
Solar Potential
High
Medium
Low
EASTERN REGION
Solar Potential
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Medium
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NORTHERN REGION
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UPPER WEST REGION

Figure 4.13 Solar Potential Maps of the various Regions of Ghana

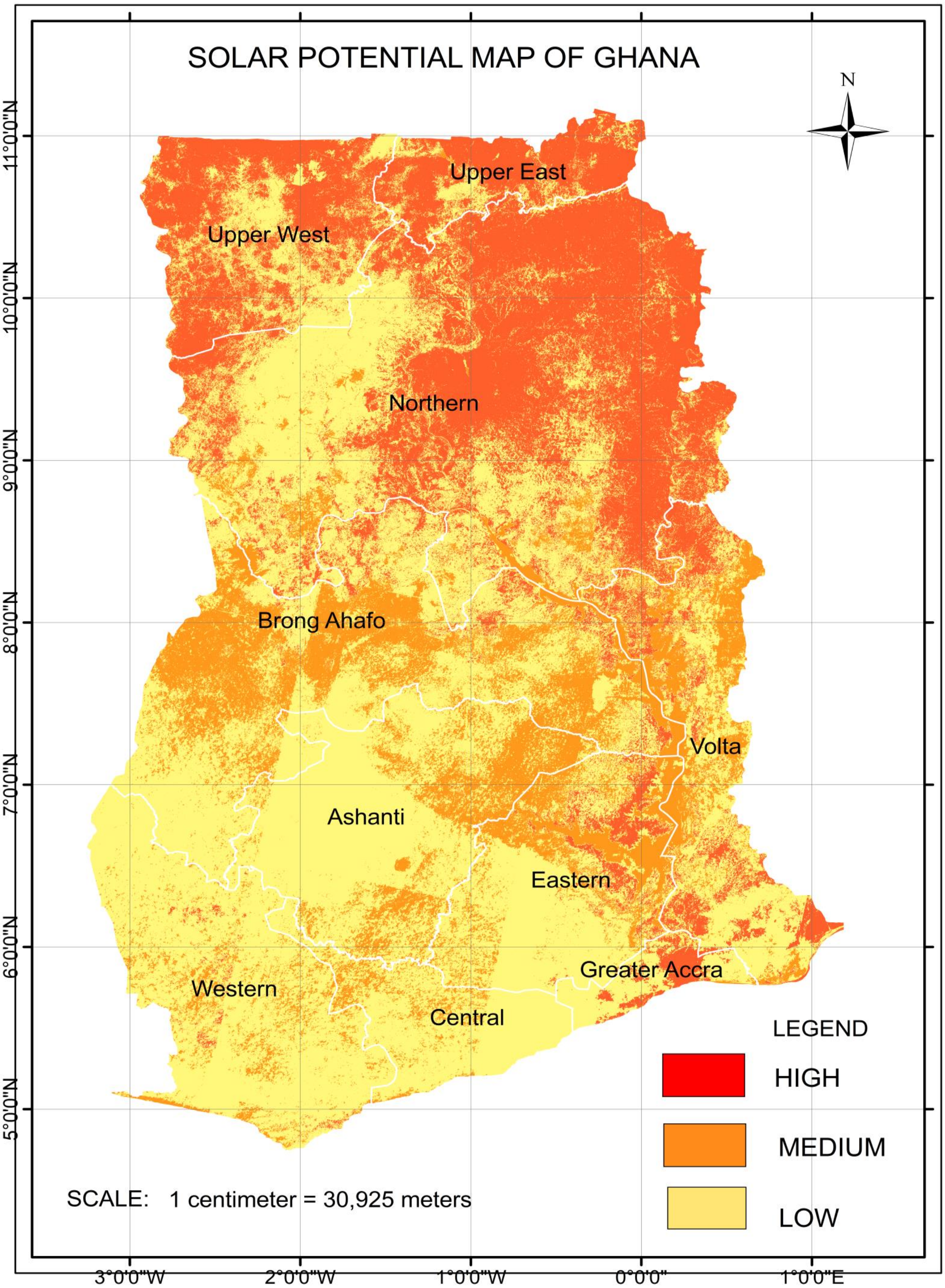

Figure 4.14 Solar Potential Map of Ghana

CONCLUSIONS AND RECOMMENDATIONS

1.14 Conclusions

Developing solar energy potential map for exploitation of solar energy to support other power sources to meet the growing demand of electricity is the aim of this research. The conclusions were drawn based on the results of the formulated objectives.

- **Objective One: To identify areas with high Global Horizontal Irradiance (GHI) of the regions for five years.**
  The solar potential derived using Google Earth Engine showed that the upper part of Ghana had a higher potential for solar radiation than that of the lower regions consistently over the five (5) years of the study. Among the regions with higher solar potential are the Upper East region, Upper West region, Northern regions and the Volta region. The higher solar radiations that incident on the surface of the earth contributed significantly in the potential value of the regions. The Northern region had a very high solar potential, followed by the upper east and upper west region. Volta region showed a fairly minimum solar potential values.

- **Objective Two: To model the identified areas with high GHI of the various regions throughout the year.**
  The estimation of Land Surface Temperature, Albedo, Solar Radiation (GHI) and the Linear Regression Analysis were modelled to reflect the solar potential of the various regions.
- **Objective Three: To create thematic solar irradiation maps for the various regions.**
  Thematic maps of solar potential for the various regions were created based on the model in objective two. These solar maps will be useful for exploitation of solar energy to support other power sources to meet the growing demand of electricity and also for decision making.

1.15 Recommendations

- Further research should be carried out to develop solar potential map of ground based recording of solar radiation data in comparison with satellite imagery.
- Further study on the various districts is encouraged to estimate the solar potentials of the districts for exploitation.

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BIOGRAPHICAL NOTES

- Sebastian Botsyo is a very determined practical person with the ability to learn new skills quickly. He possesses enthusiasm, versatility and enjoys working well as part of a team, yet he is equally at ease working on his own initiative. He was born in Hohoe in the Hohoe District of the Volta Region of Ghana. He currently lives in Digul Park, La in the La Dadekotopon Metropolitan Assembly of the Greater Accra Region of Ghana. He studied pure science at Adidome Senior Secondary School from 1994 to 1996 and continued with the study of basic education at St. Francis Teacher Training College in Hohoe from 1999 to 2002. He also studied Surveying and Mapping in Ghana School of Surveying and Mapping (GSSM) in Accra from 2003 to 2006 and proceeded to pursue Geo-Informatics with specialization in Geographic Information System(GIS Operations) from 2011 to 2012. He is also offered BSC in Geomatic Engineering from Kwame Nkrumah University of Science and Technology. He has successfully completed a Master of Philosophy (MPhil) in Geographic Information Systems from Graduate School of Kwame Nkrumah University of Science and Technology. He is currently the Officer in Charge of Hydrographic Surveying Unit of Survey & Mapping Division, Lands Commission. He is a lecturer and Geomatic Engineer at Ghana School of Surveying & Mapping. He lectures on Surveying and Mapping principles and practical use of most surveying equipment, Geographic Information Systems (GIS), Hydrographic Surveying, Supervision of field practical in outstations, Production of cadastral plans for registration and anything related to land surveying. He is a professional member of Ghana Institution of Surveyors (GHIS), a Planning Committee member of the Annual Seminar for the Land Surveying Division of GhIS since 2013. He attended the FIG Working Week 2013 in Abuja, Nigeria, the FIG Congress 2014 in Malaysia and Turkey 2018 and presented papers at both congresses.

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