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Geospatial Analysis of Site Suitability for Solar Photovoltaic (PV) in Rwanda

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Abstract

The Government of Rwanda decided to use renewable energy to generate electricity for meeting the current and future energy demand as well as reducing greenhouse gases emissions. The Nationally Determined Contribution indicated that the adoption of solar energy related actions would reduce 8.5% of total greenhouse gases emission by 2030. In addition, the Government of Rwanda planned to increase electricity access to 100% of households by 2024. Therefore, identifying the potential locations for solar photovoltaic (PV) is essential for supporting the current country's programs of promoting the use of renewable energy. In this study, GIS as a spatial analysis tool was used based on the Multi-Criteria Evaluation (MCE) model to find the suitable locations for solar PV through the identification and weighting of the factors that affect suitability. The reclassified and weighted values were combined in a bid to produce the final suitability map for solar PV. Findings revealed that most of the Rwandan regions receive solar radiation, which is higher than 3.6 kWh/m^2 per day recommended for solar PV installation. This implies that Rwanda receives enough solar radiation to enable electricity generation. Based on analyzed criteria, results revealed that 42.48% of Rwanda territory coverage is suitable for solar PV plant and 30.58% is moderately suitable. Most of those sites were found in the Eastern and Southern Provinces of Rwanda.

Keywords: *Geographical Information Systems (GIS), Multi-Criteria Evaluation Model, Solar PV, Suitability Analysis*

1. Introduction

Greenhouse gases emissions have risen dramatically since the start of the industrial revolution in 1760s (IPCC, 1990). The total accumulation of those gases in atmosphere has led to the global warming that is proven with the increase of global temperature about 1 degree Celsius in the period of 100 years (NASA, 2009). Globally, the primary source of greenhouse gases are related to the combustion of fossil fuels, whereby 75% of the global carbon dioxide emissions are produced for

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the transformation and use of energy (Steen, 2017). Mainly, the fossil fuel combustion are done for electrical production, and this account for 10 gigatonnes of carbon dioxide equivalent (CO_2e), which is approximately 37% of global emissions (WNA, 2011). The emissions would continue to rise if no mitigation actions are adopted, because electricity generation accounts for 40% of the total global energy consumption and electric demand is expected to increase by 43% over the next 20 years (Rahman & Castro, 1995; WNA, 2011).

As one of the solutions, the viable alternative to reduce this threat is the adoption of renewable energy. This is not only supposed to reduce the greenhouse gases emissions, but also helps to meet the high energy demand in the future and attain sustainable development (M. Hassaan et al., 2020). In this respect, many types of renewable energy have become feasible and viable in recent years because of rapid technological advancement, such as solar, wind, hydro, geothermal, etc. Among them, solar energy is one of the most inexpensive, reliable, safe, and available energy, and is particularly recommended to be used for the regions with enough solar radiation (Dapueto et al., 2015). In fact, solar energy provides abundant energy that could meet growing demand for electric power in many countries, cut high emissions and offer carbon credits (Dejan Doljak & Gorica Stanojević, 2017).

Some countries have successfully adopted solar energy. For example, Singapore has installed solar capacity of 0.4 megawatt peak (MWp) in 2008 to around 143 MWp in 2017 (Ministry of Foreign Affairs, 2018; NCCS, 2021). Despite challenges, such as limited land and intermittency in generation due to high cloud cover, solar photovoltaic (PV) deployment in Singapore has grown rapidly. It was successfully implemented, after identifying solar as the most viable clean energy source for local deployment in terms of technical feasibility and cost. Another crucial initiative was to invest in the research, development and demonstration of solar PV and related technology (Ministry of Foreign Affairs, 2018). As China's energy consumption is expected to increase at 60% by 2030, it has adopted the solar energy facilities of 253 GW photovoltaic capacity by the end of 2020, and this accounts for one third of global photovoltaic capacity (IEA, 2015; IRENA, 2014). Although solar energy is clean, and the cost of producing is low, its adoption rate is still low (Cengiz & Mamiş, 2015). Various challenges hinder the adoption and diffusion of solar energy especially in developing countries. Among them, is to find the suitable locations for solar PV projects (M. A. Hassaan et al., 2021; Rodrigues et al., 2017; Suprova et al., 2020; Tisza, 2014). Also, the limited skills about solar technologies leads to planners not recommending photovoltaics for new buildings (Karakaya & Sriwannawit, 2015). In some countries and regions, climatic conditions, land requirement and architectural constraints make solar less practical than in others (De Marco et al., 2014). In addition, a lack of stability of incentives for the adoption of solar photovoltaics, high initial costs of the solar PV modules and high installation makes developing countries not adopting the solar energy (Karakaya & Sriwannawit, 2015).

Africa's solar PV capacity has increased in recent years, but from a low base. The installed capacity at the end of 2014 was 1,334 megawatt (MW), more than ten times larger than in 2009 (127 MW).

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Africa has enough solar radiation to enable the solar energy generation, for example the desert regions of North Africa and some parts of Southern and East Africa receive enough solar radiation (IRENA, 2015). As many people in Africa live in rural areas where they don't have access to the on-grid electricty, the mini-grid solar PV systems are also used for solar street lighting, mobile-phone charging stations, telecom towers and solar irrigation pumping water (IRENA, 2015). As approximately 600 million Africans are currently living without access to reliable energy services Therefore, solar energy will be a solution for bringing affordable energy to the African population (IRENA, 2020).

Rwanda, as a country which embarked to mitigate climate change has installed on-grid energy capacity of 12.230 MW from 5 solar power plants namely Jali power plant which generate 0.25MW, Rwamagana Gigawatt generating 8.5 MW, Ndera Solar power plant generating 0.15MW and the Nasho Solar plant generating 3.3 MW (RURA, 2019). In 2019, the annual report of Rwanda Utility Regulatory Agency indicated that in the energy mix, the solar energy accounted for 2% of the total (RURA, 2019). Considering the target of Rwanda to cut off 38% of emissions by 2030, and electrify 100% of households by 2024, it is clear that the solar energy use is still low and there is a need to improve and deploy many solar PV stations to achieve the emission reduction and energy demand targets (Republic of Rwanda, 2020). As of September 2021, the access rate of electricity is 67% of Rwandan households including 48.6% connected to the national grid and 18.5% accessing through off-grid systems (REG, 2021a). In fact, solar energy depends on the amount of solar radiation, the area of suitable land and power generation efficiency (Suprova et al., 2020). Various studies (Hagumimana et al., 2021; Hakizimana et al., 2020; Museruka & Mutabazi, 2007; Bonfils Safari & Gasore, 2009) have been conducted to analyze the potential of solar technology and estimation of global solar radiation in Rwanda, in addition Solargis (2021) has published the solar resource map, showing the solar radiation in Rwanda (Solargis, 2021). However, there is still a gap of identifying the most suitable or most favorable places for solar Photovoltaic (PV) installation by considering different factors beyond the solar radiation factor. This study intended to assess the solar radiation in Rwanda, and analyze other factors to indicate the suitable areas for solar PV. Geographic Information System (GIS) has been used to analyze different criteria by using multi-Criteria evaluation model, this helped to produce the suitability map for siting the solar PV in Rwanda. This will inform the potential investors and renewable energy developers about the suitable place, where the solar PV can be deployed and used in a sustainable way in Rwanda.

2. Materials and Methods

2.1. The Study Area

The study area for this study is Rwanda, which lies between 1°4′ and 2°51′south latitude, and 28°53′ and 30°53′ east longitude and it covers an area of 26,338 km^2. The topography of Rwanda is ascending western ward from 1000 meters to 4507 meters where the central plateau region range from 1,500 m and 2,000 m and the eastern plains elevation range from 1,000 m to 1,500 m. The Congo-Nile Ridge located in western province near Kivu lake and volcanic chains of Birunga have the elevation varying between 1,800 m, 4,507 m, while the low elevation is found at Bugarama plains in south western at 900 m (Muhire et al., 2015). In Rwanda, the low temperatures are received in higher elevations of the central plateau between 17.5 - 19°C, while the warmest annual average temperatures are found in the eastern province ranging between 20 - 21°C, Bugarama plain receives the temperature between 23 - 24°C, while the highlands have the temperature less than 17°C (RMA, 2021).

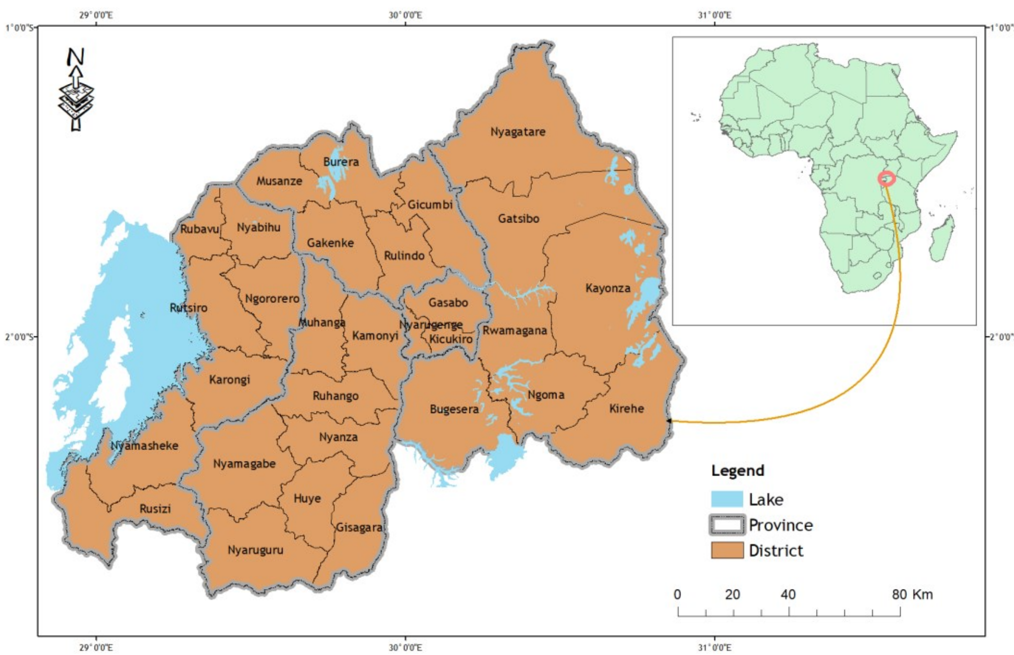

Figure 1: Location map of study area

2.2. Literature review

The literature review was done mainly with the purpose to identify the problems underlying in the solar energy and the gaps to be filled. An initial step in the process was to conduct a desk review to get insights about the potential use of solar energy and its contribution in energy mix. National documents such as annual reports from Rwanda Utility Regulatory Agency and Rwanda Energy Group were reviewed to understand the status of solar energy in Rwanda. In addition, Nationally Determined Contribution submitted to the United Nations Framework Convention on Climate Change (UNFCCC) by Rwanda in May 2020 was reviewed to know the contribution of solar energy in reducing the quantity of greenhouse gases emissions by 2030. Furthermore, journal articles were reviewed to understand the barriers in deploying solar energy.

2.3. Geographic Information System

In this study, GIS was used in suitability analysis for solar PV sites, whereby it involved the use of several geographical datasets as shown in Table 1. The dataset to be used for geospatial analysis, were selected based on the factors that determine the suitable areas for solar installation. These factors were divided into three categories: (i) productivity factors; (ii) territorial constraints; and (iii) exclusionary areas (Rodrigues et al., 2017). The productivity factors are conditions that allow the solar PV to generate high quantity of electricity, and those factors were used as weighted variables for the suitability analysis (Rodrigues et al., 2017). Some areas were qualified as territorial constraints for installation of solar PV, because they have low degree of preference for installing the solar farms. For instance, high slope areas, built-up areas, and other areas far from transmission lines and roads. In addition, other areas were considered as exclusionary areas because they cannot be used for solar PV installation, such as lakes, rivers, wetlands, and national parks.

Table 1: Dataset used in the study

Type	Theme	Format
PF	Digital Elevation Model	Raster
PF and TC	Transmission Power lines	Vector
PF and TC	Road Network	Vector
TC	Rivers and Lakes	Vector
TC	Urban areas	Raster
TC	Protected areas/forest (National Parks)	Vector
N/A	Country boundary	Vector
PF	Global Horizontal Irradiation	Table

PF – Productivity Factor; TC – Territorial Constraints - N/A not applicable

2.4. Multi-Criteria Evaluation Model

Multi-criteria evaluation in GIS is the method for allocating the land suitable for a specific activity on the basis of a variety of factors that the selected areas should comply with (Koc et al., 2019). This method was particularly used because land suitability analysis for solar PV requires considering different criteria as shown in Table 2. Multi-criteria evaluation in GIS is a tool used to produce the final suitability map of Rwanda. Figure 2 present the framework used to analyze the suitable sites for solar PV in Rwanda.

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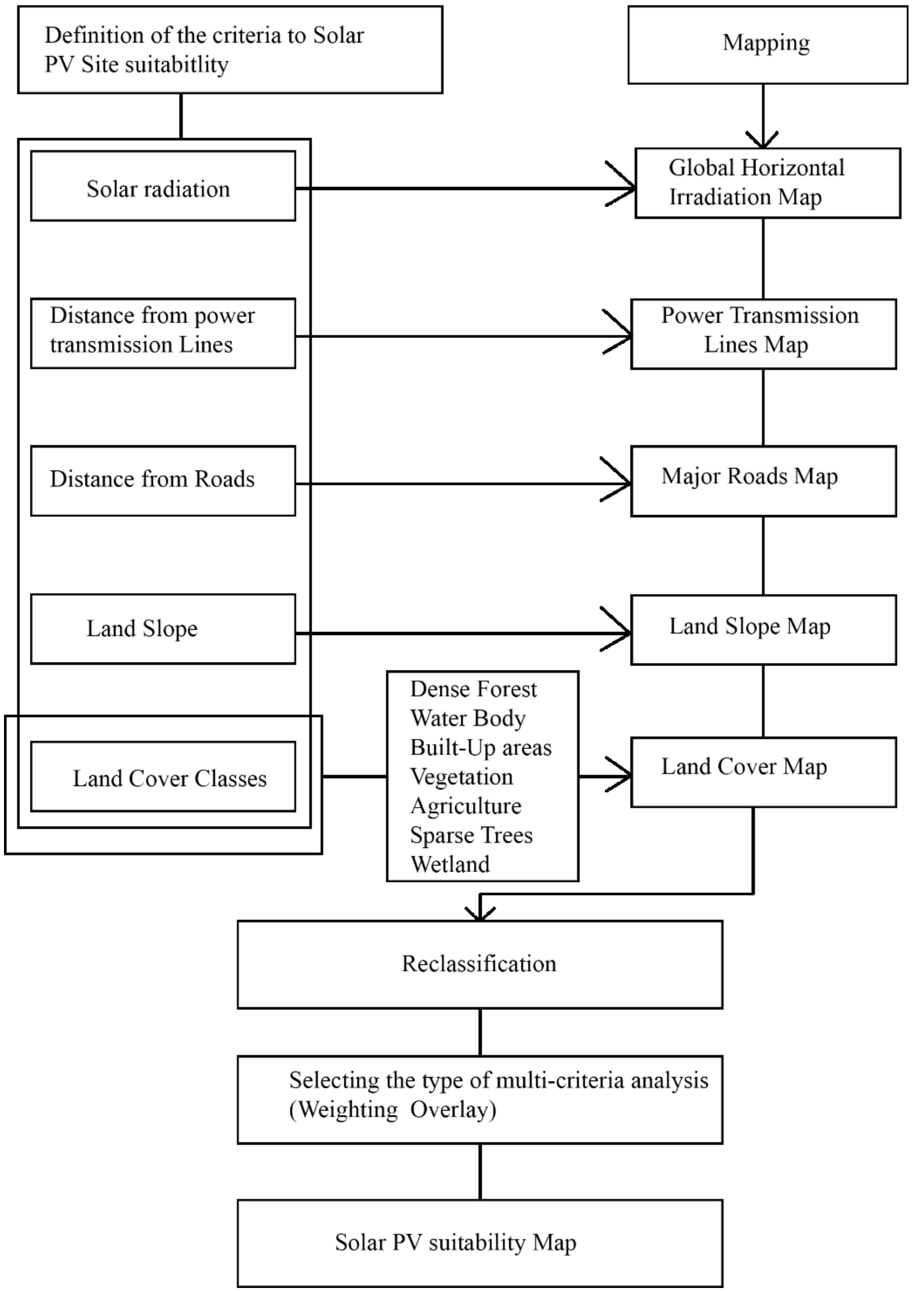

Figure 2: Framework for finding the suitable site of solar PV in Rwanda

After identifying the criterion to be used in the model, they were weighted according to their importance. Reclassification was done for each criterion at the weight scale laying from 1 up to 9. On this scale of importance, 1 refers to lowest, 3 to low, 5 to average, 7 to high, and 9 to highest by referring to the threshold value of the criterion. The intermediate values (2, 4, 6, and 8) were used, when the criterion score is not equal the exact importance level mark above mentioned. Weight overlay tool from ArcGIS was used to combine each criterion to produce the solar PV suitability map.

Table 2: Scores and weight of selected criterion for terrain, solar radiation, and proximity to power transmission lines and roads

Criteria	Rank	Range	Weight	Threshold	Unit	Reference
Slope	Very High High Moderate Low Very Low	0 - 5.97 5.97 – 12.76 12.76 – 20.09 20.09 – 28.78 28.78 – 69.24	20%	<12	%	(Elboshy et al., 2021)
Solar radiation	Very High High Moderate Low Very Low	5.23 – 5.55 5.04 – 5.23 4.81 – 5.04 4.52 – 4.81 3.52– 4.52	30%	>3.6	kWh/m²/day	(Elboshy et al., 2021)
Proximity to power lines	Very High High Moderate Low Very Low	< 2 2 – 5 5 – 10 10 – 20 20 - 30	10%	<5	Km	(Elboshy et al., 2021)
Road network accessibility	Very High High Moderate Low Very Low	< 2 2 – 5 5 – 10 10 – 20 20 - 40	10%	<5	Km	(Elboshy et al., 2021)

Table 3: Weight of selected criterion for land cover classes

Criteria	Factor	Reference	Weight
Land cover classes	**Excluded areas:** Water body, wetland, and national parks (forest)	(Bizoza & Ndangiza, 2014)	30%
	Territorial constraint: Built-up areas	(Rodrigues et al., 2017)	

3. Results

The used methods produced the results that helped in generating suitable site map for solar PV installation. Some interpreted data were retrieved from free database such as ESRI Global Land use and land use change maps, and Global Solar Atlas.

3.1. Solar radiation

The solar radiation is important to understand the amount of solar energy available for electricity generation, and any other energy applications such as solar irrigation (B. Safari & Gasore, 2009). In this study, the Global Horizontal Irradiation was considered because it is the most important parameter for energy yield calculation and performance assessment of flat plate photovoltaic (PV) technologies (Cony et al., 2011). The Global Horizontal Irradiation is the total amount of shortwave radiation received from above by a horizontal surface (Hagumimana et al., 2021). Therefore, it can help to understand the amount of solar radiation available for use.The solar radiation was sourced from global Solar Atlas (Solargis, 2021). The data represents the average daily/yearly sum of Global Horizontal Irradiation (GHI) covering a period of 1994-2018. The map of global solar atlas was produced by considering three main models, namely the solar radiation model, air temperature model, and PV power simulation model. The table with global horizontal irradiation data has been retrieved and the map was produced as shown on Figure 3.

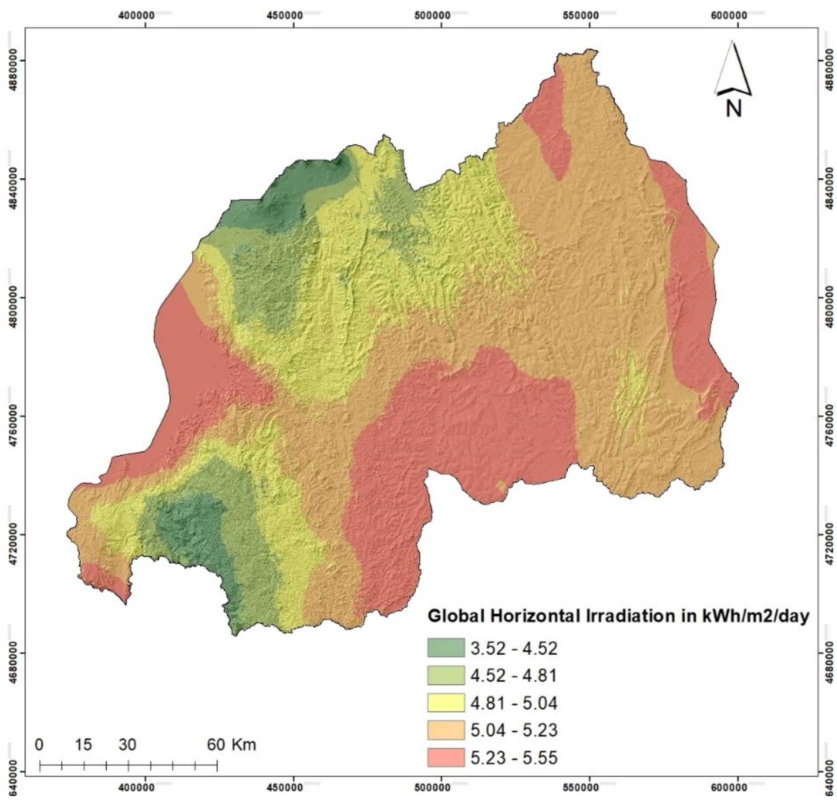

Figure 3: Map of Global Horizontal Irradiation for Rwanda
Data source: Global Solar Atlas, data accessed on 15 August 2021

Figure 3 indicates that the highest Global Horizontal Irradiation (GHI) varied between 5.23 and 5.55 kWh/m^2 per day. This solar radiation is received in parts of Eastern region of Rwanda such as Nyagatare, Bugesera and Rwamagana Districts, parts of southern areas of Kigali, and district of Nyanza, Huye, Gisagara, and Kamonyi in South. In addition, the areas near the Lake Kivu in

Western Province get high solar radiation that range from 5.23 to 5.55 kWh /m^2 per day. The districts in the Northern Province received solar radiation that ranges from 4.52 to 5.04 kWh / m^2 per day. The lowest Global Horizontal Irradiation have been found in northern west and southern west of Rwanda ranging from 3.52 to 4.52 kWh /m^2 per day.

3.2. Suitability analysis for siting solar PV

This study has detailed the suitability analysis for siting solar PV, as shown on Table 2, different criteria were considered to run a model for Multi-criteria Evaluation and the results from mapping the different criteria considered are described below.

a. Terrain Criteria

The analysis of the suitable areas for solar PV installation considered the slope of terrain factor. The slopes was calculated on Rwanda Digital Elevation Model (DEM) raster surface.

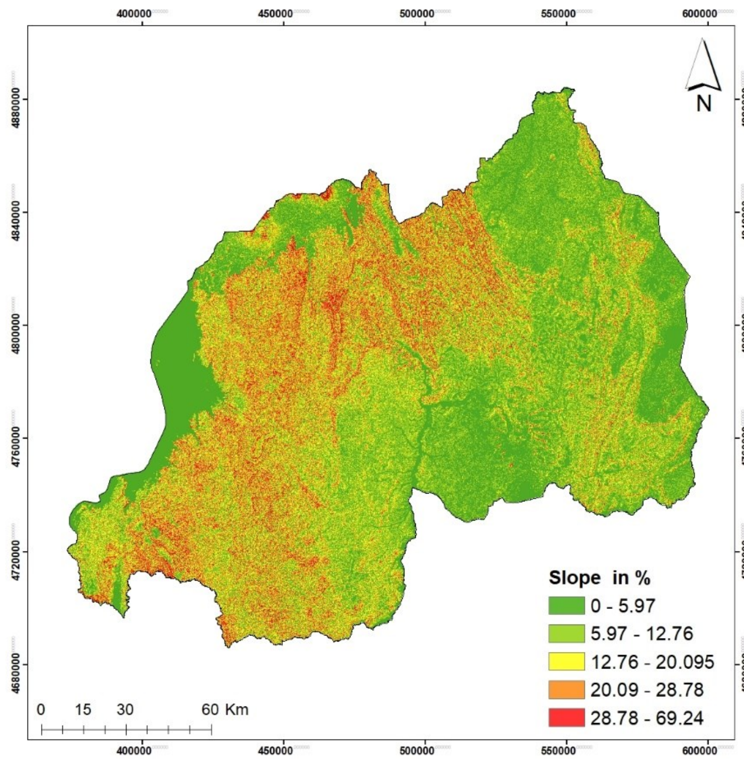

Figure 4: Slope map of Rwanda

The map shows that the western part of Rwanda has steep slope ranging between 28.78% and 69.24% which is mostly unsuitable for solar PV installation. The areas of Eastern and Southern Province which has the slope from 5% to 12% proven to be suitable for Solar PV based on the slope factor.

b. Land use criteria

In this study national parks, wetland and water bodies (lakes and rivers) were restricted in the suitability analysis, while the urban areas were scored low for being a suitable sites. In fact, national parks and water bodies are reserved for ecosystem and environment protection, whereas the urban areas have the high cost of land (Bizoza & Ndangiza, 2014). The figure below show the land cover map of Rwanda in 2020.

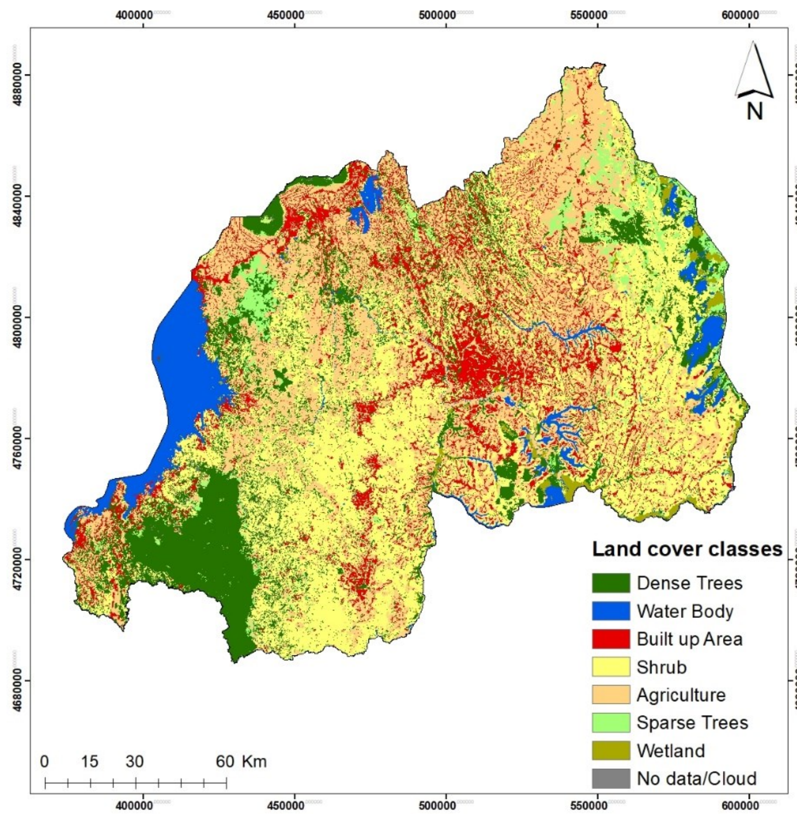

Figure 5: Land cover map of Rwanda in 2020
Source: ESRI, accessed on 20 July, 2020

c. Transmission Network Criteria

The transmission network is an important factor for distribution of electricity from solar energy. The study considered the road network, mainly the national and district road. Beside, the study considered the power transmission lines in the country. The criteria was to have an area within 5km from the road and powerline. The euclidean distance tool from ArcGIS was used to calculate the areas which are suitable from those 2 lines network. The advantage of solar energy being in the proximity of road network and existing powerlines, is the low operation cost during installation and maintainance as well in electricity distribution (Karakaya & Sriwannawit, 2015). The map below show the road and power transmission line coverage in 2 and 5 km as suitable sites.

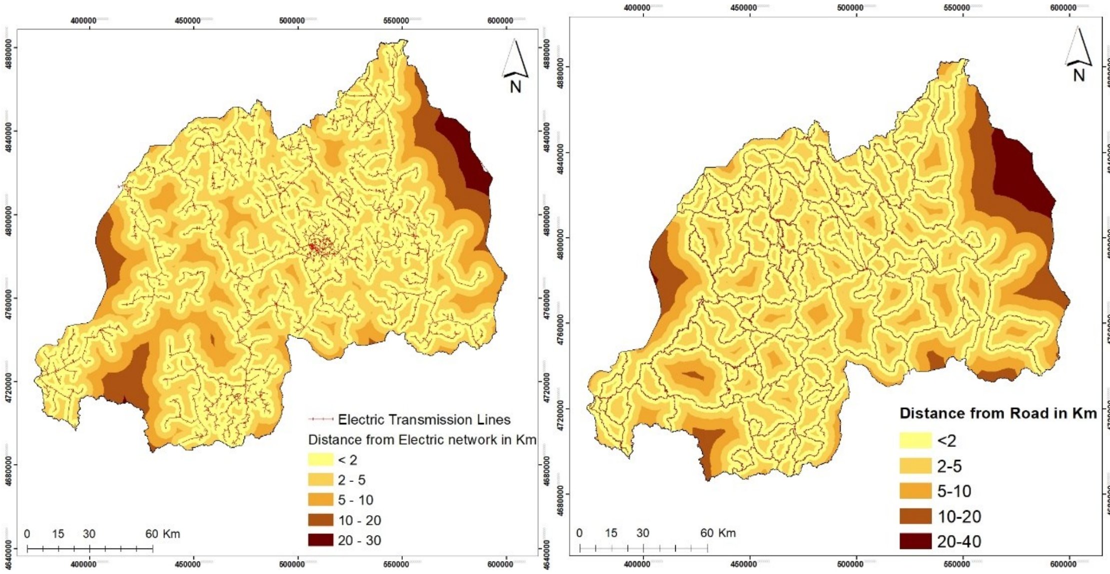

Figure 6: Distance from electricity transmission lines (left) and main roads (right) maps

3.2.1.1. Solar PV suitability map

To generate the final suitability map, the weight overlay has been applied and weight was assigned to each criteria as indicated in Table 2. As shown on Figure 7, the most suitable areas are located in Eastern and Southern provinces.

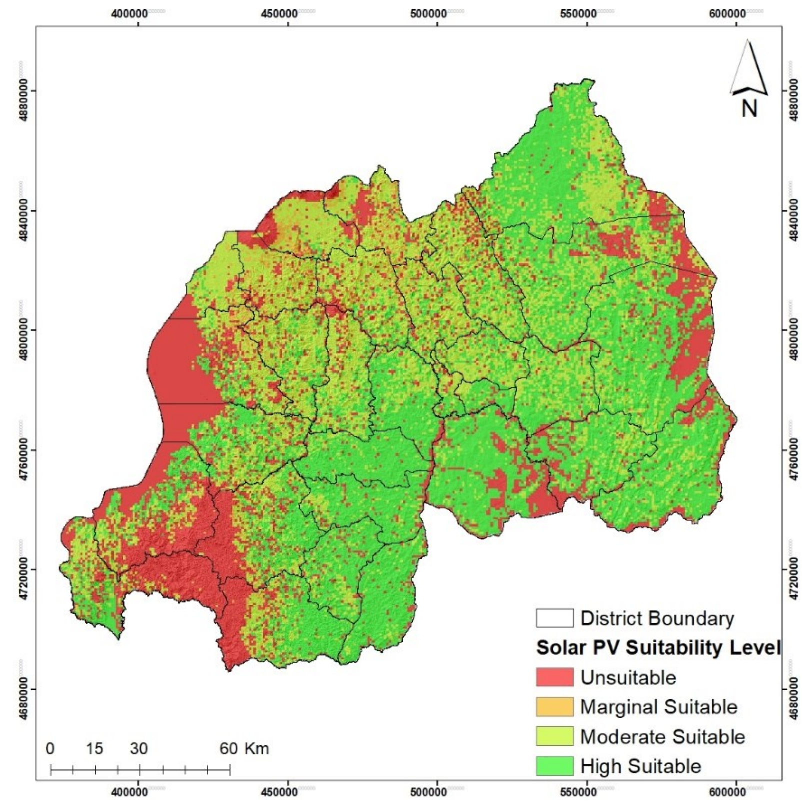

Figure 7: Solar PV suitability map

Table 4 presents the areas with their respective percentage of each category for suitability level. the findings indicated that the territory that can potentially be used for a solar PV is 42.48% while 30.58% is for moderately suitable, and this gives 73.06% of the total area of Rwanda by considering the moderate and highly suitable areas. The findings indicated that 9 districts namely Ruhango, Gisagara, Huye, and Nyanza in Southern province, Ngoma, Gatsibo, Kirehe, and Bugesera in Eastern Province and Kicukiro district have a good coverage of solar PV suitability above 60% (considering the moderate and highly suitable areas) as it shown on Figure 8.

Table 4: Areas for each suitability level category

Solar PV suitability level	Areas	Percentage
Unsuitable	6,336.01Km^2	25.1%
Marginal Suitable	464.88Km^2	1.84%
Moderate Suitable	7,726.89Km^2	30.58%
Highly Suitable	10,732.6Km^2	42.48%

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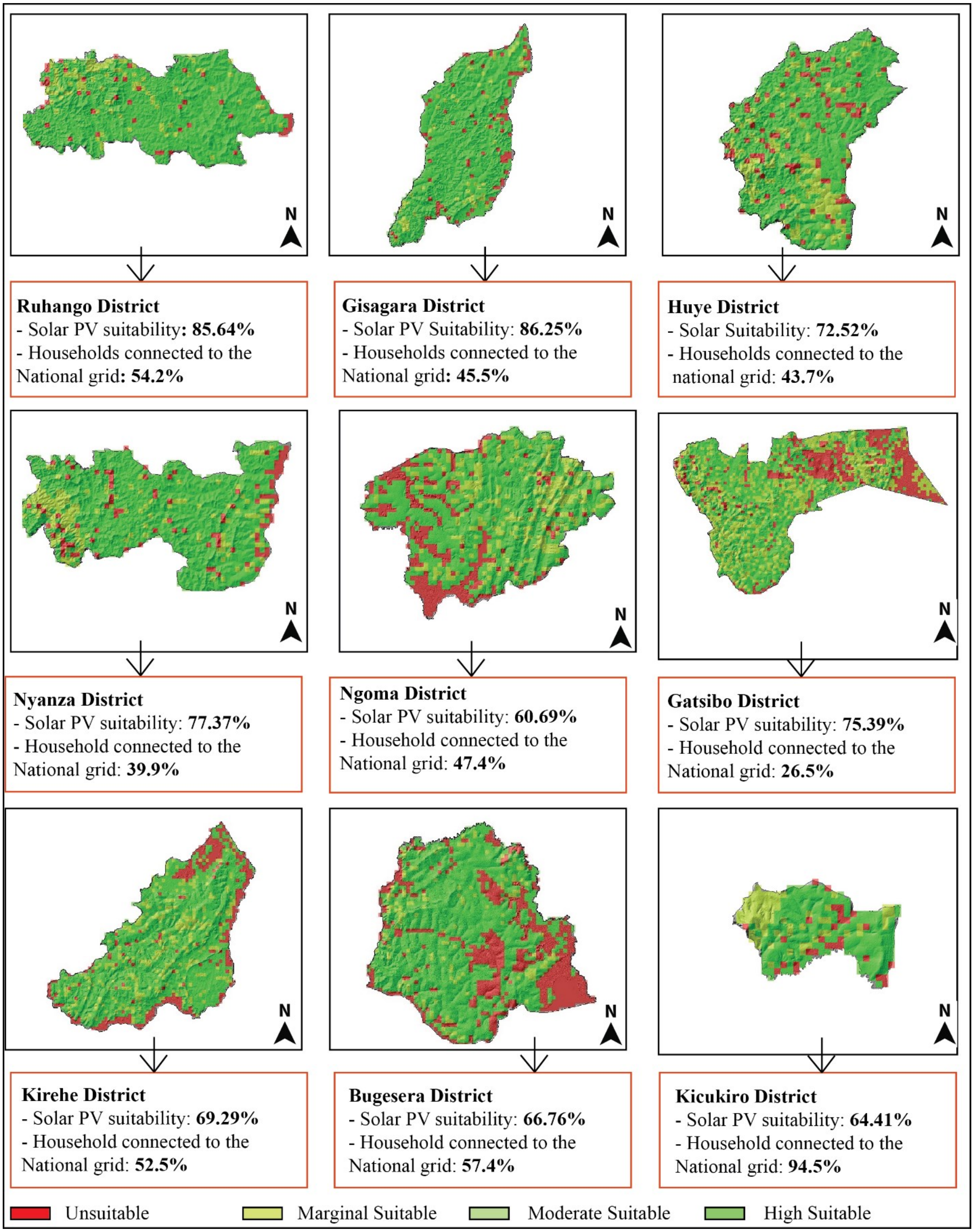

Figure 8: Districts with high suitability level of solar PV and their respective percentage of households connected to the national grid

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4. Discussion

The result indicated that the areas of Rwanda receive solar radiation ranging between 3.52 and 5.55 kWh /m^2 per day. This result demonstrates a correlation with the findings reported by (Museruka & Mutabazi, 2007) whereby the global solar radiation calculated varied between 4.3 to 5.2 kWh/m2/day on Kigali Meteo station. It was done by validating the satellite dataset measurements taken over a 10 year period (1984 to 1993). In addition, another research found the annual solar radiation value of 5.26 kWh /m2/day by using the empirical model to be in the range of 3.52 and 5.55 kWh /m^2 per day (Bonfils Safari & Gasore, 2009). The research revealed that the solar PV would be effectively applied in the areas that receive the solar radiation preferably above 1300 kWh/m^2/year, which is approximately to 3.6 kWh/m^2/day (Elboshy et al., 2021). Solar radiation is the essential criteria since it determines the output electricity generation from solar PV. As Rwanda has the potential sites with solar radiation above 3.6 kWh/m^2/day, this implies that Rwanda receive enough solar radiation to enable electricity generation from solar PV. However, as the received solar radiation is not a sole factor to be considered in suitability analysis, there are other criteria considered to decide the suitable areas namely terrain factor (slope), transmission lines (electric lines and roads), and land cover classes, (built up areas, water body, wetland, forest).

The findings show that solar PV could contribute to the increase of electricity access rate, based on good coverage of suitable sites at 73.06% of Rwanda territory (considering the moderate and highly suitable areas). Solar energy could be a potential source of energy to increase the access for the household connected to electricity, as of September 2021, the access rate of electricity was 67% of Rwandan households including 48.6% connected to the national grid and 18.5% accessing through off-grid systems (REG, 2021a). Taking advantage of good coverage of suitable sites for solar PV will help households to connect to the solar off-grid system, which can benefit rural and remote areas. For example, the findings indicated that nine districts have good coverage of solar PV sites above 60%, and they have below 60% of households connected to the on-grid system. In this respect, Ruhango, Gisagara, Nyanza and Gatsibo are the four districts that can benefit most from the solar PV because their suitability coverage are 85.64% , 86.25%, 77.37% and 75.39% respectively, while the households connected to the on-grid system are 54.2%, 45.5%, 39.9% and 26.5% respectively (REG, 2021b). In fact, the use of multi-criteria analysis proved to be a good option for modeling the suitability analysis of solar PV, because it allowed the consideration of various factors to get a suitable site. The multi-criteria analysis combined the various weighted criteria with spatial representation into a single suitability map, and this provided valuable information for helping potential investors and renewable energy developers on the sites to install the solar PV.

5. Conclusion

This study intended to analyse the suitable sites of solar PV installation in Rwanda by considering various factors including the solar radiation, land cover, transmission lines (main roads, electric lines), and terrain factor (slope). Given that solar energy is one of the climate change mitigation measure, that have been selected in Nationally Determined Contribution submitted by Rwanda to the United Nations Framework Convention on Climate Change, this study contribute to solar energy adoption by indicating the areas in which solar PV can be installed to produce the energy without degrading and conflicting other important land use. The results from this study indicated that the areas of Rwanda receive sufficient solar radiation between 3.52 to 5.55 kWh /m^2 per day, which is beyond the 3.6 kWh/m^2 per day recommended amount for installing the solar PV. It was found that the suitability of the study area for a solar PV is 73.06% of the total area of the country by considering the moderate and highly suitable areas according to the criteria analyzed.

Considering different criteria divided into three categories, as productivity factors, territorial contraints and exclusionary areas helped to produce the solar PV site suitability map. This map will inform potential investors, renewable energy developers, decision makers, planners, on the best suitable sites for solar PV projects. In fact, the big picture was not to decide which the "best and specific suitable location" instead, the main aim was to make available an explicitly spatial approach to enable an informed discussion with the stakeholders. It is important to note that, this approach can easily be adapted to include more constraints or other criteria in the modeling process for any specific project on solar PV as such projects consider technical, environmental, economic and social factors.

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