Harvesting Renewable Energy to Meet Jamaica's Electricity Demand by 2030: The Case for Solar Energy

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1. Abstract: The main objectives of the study are to explore the impacts of appropriate locales for ground-mounted solar PV systems expansion to reduce dependence on fossil fuels in energy generation and to estimate the potential carbon dioxide emissions reduction to address climate change concerns. A comprehensive analytical framework is developed utilizing the Analytical Hierarchy Process with the integration of two multi-criteria evaluation approaches, Multi-Criteria Decision-Making Methodology (AHP-MCDM) and Fuzzy Logic (AHP-FL). To address the local landscape the study includes socioeconomic, safety, environmental, technical, geographic, and legal assessments in the Geographic Information Systems environment of Arc-GIS 10.8.1 software. Twelve constraints and factor variables were used to determine appropriate weights based on experts' and stakeholders' opinions. The vector and raster data sets were gathered from various ministries and international organizations including, Global Solar Atlas, and the Jamaica Meteorological Service Division (metServiceJA) of the Ministry of Housing, Urban Renewal, Environment, and Climate Change. Solar radiation data and algorithms from Solaris are used with digital images gathered from various satellites, Meteosat PRIME and IODC, GOES-East, and West, MTSAT, Himawari-8, MACC-11/CAMS atmospheric data, MERRA-2 atmospheric data, Copernicus, and GFS. Thereafter geoprocessing was done to convert files to raster by reclassification into four distinct classes, not suitable, marginally suitable, moderately suitable, and most suitable. The results indicate a high potential for the installation of utility-scale PV solar farms since 26% of the total land area is available for renewable energy (RE) development without prohibitions. The two best sites are Chateau in Clarendon, and Islington in St. Mary with a potential capacity of 152,121.47 GWh/km²/yr. from 3.996 km² land and 38,028.94 GWh/km²/yr. from 4.162 km², respectively. These sites boast annual mean daily global solar radiation of 19.28 and 19.26 MJ/m²/day correspondingly. Additionally, the expansion of solar photovoltaic (PV) systems can result in cost savings of USD 3,938,289.96 from a reduction in 61,535 barrels of oil (BOE) importation and a potential CO_2 emission reduction of 49,228.62 MTCO2eq/yr. This research will aid policymakers to promote sustainable development whilst taking advantage of domestic resources, and cost-effectively addressing climate mitigation amongst other local environmental goals.

Keywords: renewable energy, solar PV systems, Geographic Information System (GIS), Multi-criteria Decision-Making Process (MCDM)

1. Introduction

Globally energy systems are undergoing a period of transformation as countries work towards decarbonizing their energy supply to address the anthropogenic impacts of climate change. The energy portfolio diversification has led to countries boosting RE outputs through increased deployment of solar energy systems which is the third fastest growth among renewables in the past 10 years owing to the reduced production and installation costs [1], [2]. In 2020, the estimated increase reached 156 TWh with solar PV accounting for 3.1% of global electricity [3]. Nonetheless, Jamaica's solar-based electricity output is comparably low in correlation to other energy sources, contributing 1% to national energy output and 7% of the 19% by renewables, see Figure 1 [4-7].

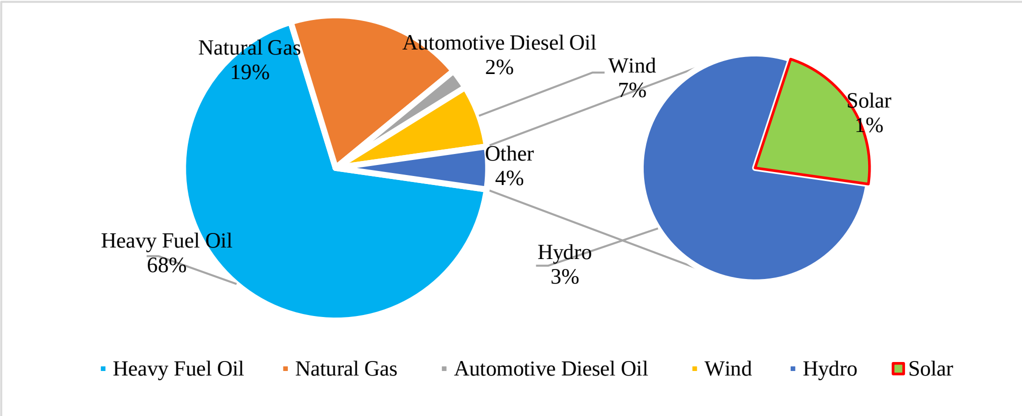


Figure 1. Jamaica's electricity generation mix as of 2020
Sources: Energy Division, Ministry of Science Energy and Technology 2018, United States Department of Energy 2020, Ochs et al. (2013), and Richards & Yabar 2022 [4-7].

Despite the late integration of solar systems into the energy mix, there has been steady growth with increases from 20 MW in 2018 to 90 MW in 2019 and 93 MW by 2020. The reduced cost of solar PV panels, steady local growth, and low utilization of 11% total capacity [8] lead to a forecast of rapid increase. Growth in PV solar systems will aid Jamaica in achieving the national development goals for 2030 declared in the National Development Plan—Vision 2030, plus RE goals of 50% by 2030 following Prime Minster Andrew Holness's instructions [9]. Moreover, increases will aid in reducing the carbon footprint of the energy industry by 6.3% as planned in the Nationally Determined Contribution under the United Nations Framework Convention on Climate Change (UNFCCC) or Paris Agreement of 2015 [10]. Heavy reliance on imported petroleum, which covers more than 70% of energy input also ignites the call for increased renewables. Recently, the government has called for investments in renewables including solar energy in the JAMAICA ENERGY INVESTMENT GUIDE [11]. Furthermore, it signed a financing agreement for solar energy projects in 2015 to boost RE generation [12].

The aims of the study are to (1) provide useful spatial information that highlights areas for ground-mounted PV solar systems, (2) produce a solar atlas with coordinate points of the most suitable sites for utility-scale solar farm (USSF) expansion, (3) assess the amount of electrical energy that can be generated from appropriate locations considering, ecological, geomorphology, socioeconomic, safety, technical, and climatology factors, and (4) compute the number of barrels of petroleum (oil) and carbon dioxide equivalent reduction contingent on the proposed scenarios.

The study's approach utilizes international standards to integrate areas with high horizontal irradiance on the island with local conditions to optimize solar energy while simultaneously eliminating barriers to project localization to limit constraints related to environmental damages and construction costs. The findings will assist energy planners, policymakers, and investors in meeting the National Renewable Energy Policy goals by locating optimal sites for USSF development. The methodological framework incorporates the Analytical Hierarchy Process (AHP) to ascertain factor weights based on experts' and stakeholders' opinions to develop spatial referencing with Multi-Criteria Decision-Making and Fuzzy Logic approaches to highlight the best site for USSF development. This is vital since past RE studies in Jamaica neglect to include stakeholders' opinions. Moreover, past national solar atlases fail to provide precise locations for commercial solar farm expansion. These studies also overlook environmental factors infusion for land availability assessments. Consequently, this study utilizes a comprehensive approach that addresses environmental concerns along with the inclusion of long-term time series atmospheric data of 19 years, from 1999 to 2018, also lacking in past studies. For example, those carried out by Chen et al. (1994) [13], Nation & Smith d.n. [14], and Chen et al. (2020) [15].

2. Methodology

The first steps in identifying appropriate sites for sitting USFS are to conduct a literature review, collect essential data then sort them. Thereafter, data sorting, filtering, and classification are done for the extraction and analysis of credible data. To minimize time spent and improve accuracy in data processing ArcGIS environment facilitates speedy computations for spatial distributions. The study employs ArcMap version 10.8.1 software, produced by Environmental Systems Research Institute (Esri), which facilitates multicriteria assessment through various methods including, Boolean Overlay, Weighted Linear Combination (WLC), Analytical Network, Process (ANP), Ordered Weighted Average (OWA), Technique for Ordered Preference by similarity to Ideal Solution (TOPSIS), Analytical Hierarchy Process (AHP), and Fuzzy Logic Ordered Weight Average (FLOWA) [16], [17].

The researcher chooses the applicable method based on the type of decision-makers, study conditions, data availability, and quality. The WLC and Fuzzy Logic are among the most credible straightforward techniques in the group above; whereas the AHP method is the most documented in RE site suitability analysis since it involves comparative ratings by applying weights to important influences through mathematical algebraic procedures. The latter approach also allows stakeholder inputs to derive the best comprehensive decision. It is recognized as possessing a sound mathematical foundation that has been employed in socioeconomic and environmental engineering [18]. Moreover, the technique allows multiple inputs of different classifications determined by the local conditions of the study area. Consequently, these approaches were adopted in this research. Figure 2 indicates the steps taken to complete the procedure of site suitability analysis by a scientific method. It also specifies the twelve constraints and 12-factor variables employed in the USSF site allocation.

The proposed site allowance is verified by quantifying potential energy from locations identified by applying annual global horizontal solar radiation on plane surfaces along with available land area, land availability by area factor, and efficiency of proposed PV solar systems. The equation below from the works of Doorga et al. (2019) [17], and Gastli & Charabi (2010) [19] is applied to generate potential energy for scenarios 1 to 3 and proposed sites referenced as best options for USSF expansion.

$$GP = SR \times CA \times AF \times n$$

Where, GP is the electric power generation potential per annum in GWh/year, SR stands for the annual global horizontal irradiance (GHI) received per area unit measured in GWh/km²/year, CA is the aggregate shape area of suitable land calculated in km², AF equals the amount of area which can be covered by solar panels (area factor), and n represents the effectiveness of solar systems in converting sunlight to electricity.

Contingent environmental impact assessment is expanded by quantifying the amount of fossil fuel-based energy displaced through three different scenarios by barrels of oil replaced alongside carbon dioxide decreases in metric tons per year (MT CO_{2e}/kWh) by proposed USSF installations. The final steps comprise validation of findings by sensitivity analysis (SA) plus site verification is conducted by areal imagery in Google Earth instrumented by the Landsat and Copernicus satellites through the National Aeronautics and Space Administration (NASA) and the European Commission by the European Union Agency for the Space Programme in partnership with the European Space Agency. The former serves to assess the variation of the uncertainty of the spatial scales in the output of the statistical model as apportioned quantitatively to various deviations of input sources in the model. Alternatively, the latter ensures the avoidance of economic and social costs associated with the inaccessibility of land.

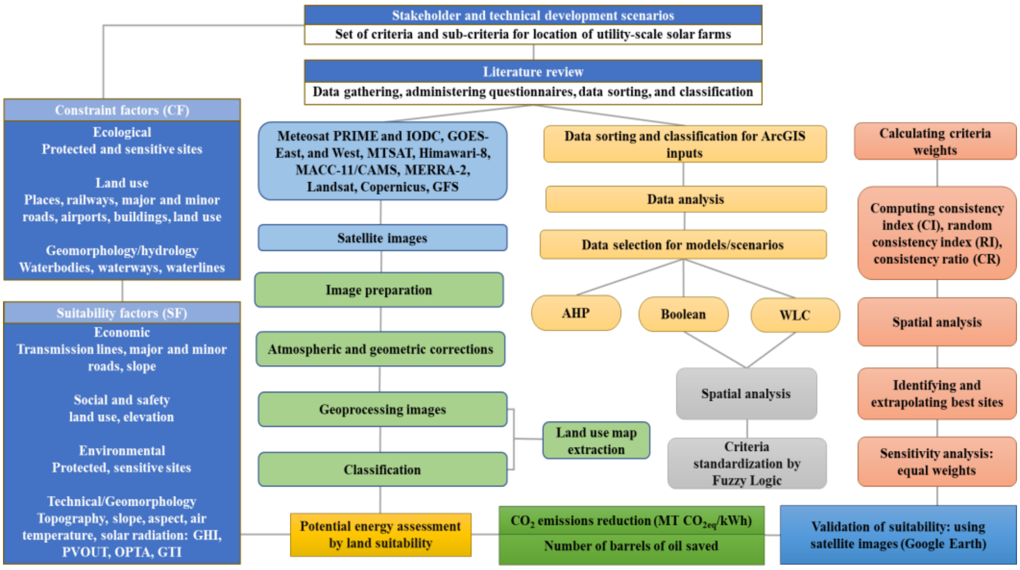


Figure 2. Methodological framework summary illustrating the steps utilized from literature review, data selection, questionnaire administration, data processing by quantification to restriction, and GIS-processing based on Analytical Hierarchy Process with Weighted Overlay Linear Combination and Fuzzy Logic applications to allocate the suitable site for utility-scale ground-mounted solar PV farms.

3. Results and discussion

This segment merges environmental, topographic, land use, accessibility, geomorphic, and selected criteria through GIS decision-making systems, then apposite locations selected. The main function is to ascertain the most suitable places for constructing USSF without confines. Thereafter, potential energy was computed from sectionalized land areas in the marginally, moderately, and most suitable zones using results from the opinions of experts and stakeholders assembled from an administered questionnaire. The potential energy from the three proposed scenarios and eleven appropriate sites were used to calculate the number of barrels of oil to be averted, associated costs, and potential CO_2 emission reduction. Variables in the restriction comprise protected and sensitive sites, places, railways, major and minor roads, airports, buildings, land use, water bodies, waterways, and water lines. Slopes, altitude, and solar atlases are prepared and then processed in ArcGIS to covert maps to digital format. After the preparation of map documents, they were merged with restriction parameters utilizing the raster calculator function in spatial analyst tools of the ArcGIS environment to derive fitting locations.

3.1. Restriction and scenario outputs

The prohibited area represents 76% of the total land area, 10,990 km² whilst the available land area for USSF expansion after restricting permanent land use and important places is 26%, 2,857.4 km², as seen in Figure 3. In scenario one, AHP-MCDM, weights are applied to twelve evaluation criteria accorded by results from 50 respondents of the questionnaire. The survey utilizes a pairwise comparison matrix of objectives and calculated weights. When the weights are applied to the variables in the suitability model underscored in Table 1, land availability reduces to 25.69%, 2,814.1 km². The most suitable class of land represents a minimal measurement of 27.32 km², 0.24%. Thus, under this scenario, 25.43% of Jamaica's land mass is useful for USFS construction. In scenario two, AHP-FL, the suitability resulted in 7.82% or 859.418 km² of unprohibited land identified as valuable with 111,664 parcels of land in the most suitable category equal to 117.73 km², 1.07% of total land. Table 2 summarizes elements of the main findings for spatial land distribution of each scenario along with the sensitivity assessment findings, then Figure 3 shows the longitudinal image of land availability within the scenarios.

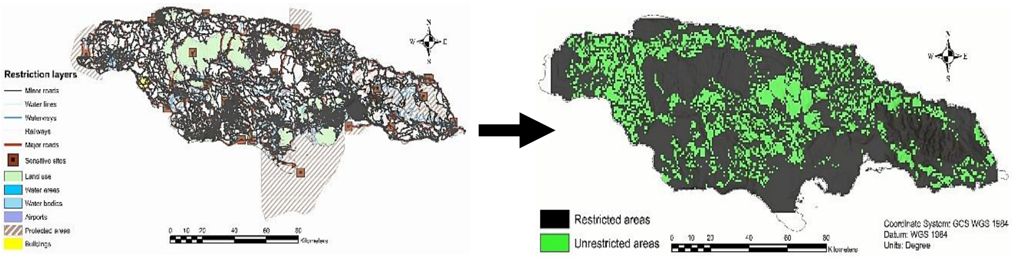


Figure 3. Jamaica's restriction map with land use and infrastructure exclusion zones

Table 1. Proportional distribution of criteria in the suitability for potential utility-scale solar farms in Jamaica

Category A	Category (criteria)	Assigned no.	Weight (%)	Category (sub-criteria)	Assigned no.	Individual weight	Cumulative weight
Level 1	Level 2			Level 3			
Solar	Economic	B1	52.53%	Distance to roads & highways	C1	73.06%	0.384
				Distance to transmission lines	C2	18.84%	0.099
				Slope	C3	8.10%	0.043
	Environmental	B2	7.12%	Distance to sensitive sites	C4	50.00%	0.036
				Distance to protected areas	C5	50.00%	0.036
	Social & Safety	B3	9.47%	Distance to land use (residential area)	C6	83.33%	0.079
				Elevation	C7	16.67%	0.016
	Technical	B4	30.88%	Solar radiation GHI (global horizontal irradiation)	C8	45.33%	0.140
				PVOUT (photovoltaic power potential)	C9	25.56%	0.078
				GTI (Global tilted irradiation)	C10	5.85%	0.018
				OPTA (Optimum tilt of PV modules)	C11	3.73%	0.012
				Air temperature	C12	19.53%	0.060
Total							1.000

Scenarios 1 and 2 are combined to produce scenario 3: AHP-MDCM -and- FL evaluation. This case eliminates repetition and affords energy planners precise information that is functional for PV solar farm planning. A total of 1,123 parcels of land parcels are accessible equivalent to 667,09 km². The most suitable classification encompasses101 parcels. However, to further downscale the results, eleven different land areas are identified with coordinate points. Locations one - Chateau, Clarendon [77°9'48.612"W 17°58'33.758"N], and two - Islington, St. Mary [76°52'12.893"W 18°20'57.898"N] are among the best choices. These land masses are detected vacant in Google Earth. Table 2 shows the potential energy to be generated by scenarios. The potential petroleum-based energy reduction for electricity generation is indicated by corresponding classes in scenarios 1 to 3, respectively. Consequently, the country will save USD 930,115.59 per year from scenario three to USD 3,938,289.96, in scenario 1.

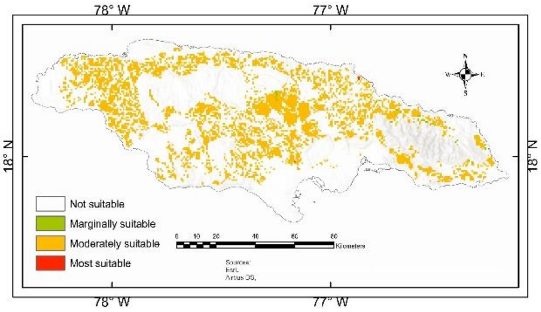
Table 2. Land suitability and potential energy output by scenarios

Suitability class	Land suitability (LS) scenarios (S)							
	S1: LS AHP-MCDM	Potential power generation	S2: LS AHP-Fuzzy Multi-Criteria	Potential power generation	S3: LS combined AHP-MCDM+AHP-FLMC	Potential power generation	S4: LS with equal weights	Potential power generation
	Total land area (m²)	(GWh/ m²/yr.)	Total land area (m²)	(GWh/ m²/yr.)	Total land area (m²)	(GWh/ m²/yr.)	Total land area (m²)	(GWh/ m²/yr.)
Not suitable	8,165,943,570	-	10,129,540,584	-	10,323,016,610	-	8,165,943,570	-
Marginally suitable	27,320,780	1,012,008.00	606,745,327	22,474,875.37	438,914,270	162,581,28.54	29,102,570	1,078,008.52
Moderately suitable	2,795,034,580	103,532,818.50	135,980,959	5,036,965.21	168,082,190	6,226,049.22	2,793,252,790	103,466,81
Most suitable	1,781,790	66,000.50	117,733,130	4,361,034.69	59,986,930	2,222,017.56	1,781,790	66,000.50

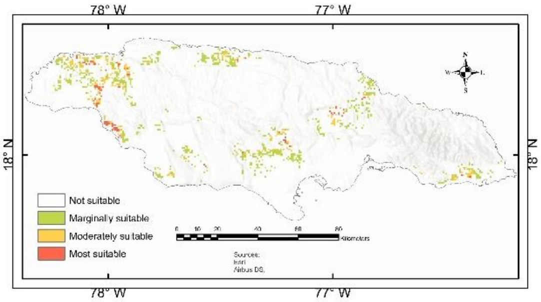
3.2. Sensitivity analysis

The sensitivity analysis shows insignificant changes occurred when equal weights are applied to the evaluation criteria in the AHP-MCDM scenario with a percentage change of less than zero. The statistical analysis of suitable land classification indicates differences of 0.06% considering not suitable and marginally suitable categories. Therefore, the estimation of suitable land remains unchanged in scenarios 1 and 3 since case 1 is the base of 3.

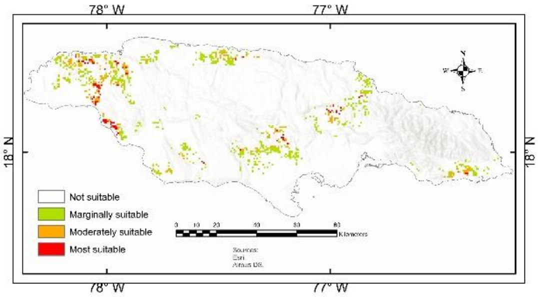
Figure 4. Land suitability for scenarios, 1, 2, 3, and 4 indicating potential sites for utility-scale solar farm construction.



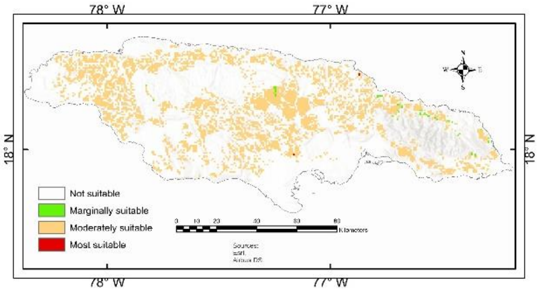
S1: Land suitability based on the AHP-MDCM



S2: Land suitability based on the AHP-FL method



S3: Combined land suitability based on the AHP-MDCM and AHP-FL method



S4: Application of equal weight with similar conditions as the AHP-MDCM approach

4. Discussion

Potential energy from selected areas and average annual solar radiation in kWh/ m²/year on the surface area shows several parishes have suitable areas for constructing USSF, see Figure 5. Silicon module solar panel was selected in the tabulation since these are the most utilized on commercial solar farms [17]. Furthermore, these have been cited as being appropriate for Caribbean islands [20]. The efficiency of these panels (*n*) averaged 27.6 in 2020 (Nyarko, Takyi, & Amalu 2020). An area factor of 70% was adopted as the maximum land area available in appropriate land areas for solar panels as recommended in studies by Doorga, Rughooputh, & Boojhawon (2019) [17], and Gastli, & Charabi (2010) [19].

Jamaica is appropriate for sitting commercial solar farms since the country has a medium to high daily global horizontal irradiation (GHI) value of 4.18 to 5.90 kWh/ m²/day and a maximum of 8.18 daily sunshine hours (computed using Global Solar Atlas (GSA) [21] and atmospheric information from Jamaica Meteorological Service Division (metServiceJA) of the Ministry of Housing, Urban Renewal, Environment, and Climate Change. This irradiance is supported by steady air temperature which fluctuates between 17.7 and 27.8 °C at 2 m above ground level, a positive as studies show at temperatures greater than 25 °C energy generated reduces by 0.4% to 0.5%. However, if temperatures are less than 25 °C the efficiency of PV systems improves [22], [23].

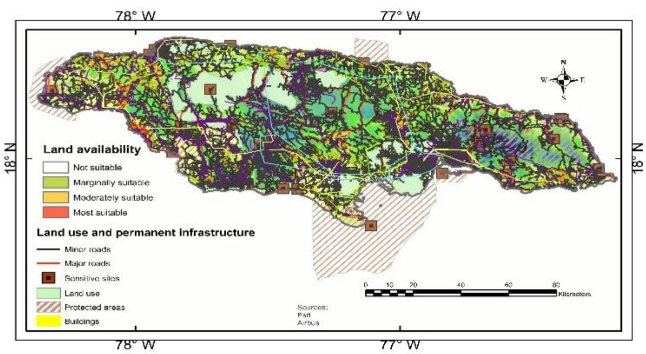


Figure 5. Fuzzy Logic showcasing site appropriation for commercial solar farms

5. Conclusion

The research concludes expansion of large-scale utilization of solar for electricity is feasible for Jamaica. This change will promote sustainable development, take advantage of domestic resources, and simultaneously cost-effectively address climate mitigation since scenarios 1 to 3 reduces CO_2 emissions by 49,228.62; 14,999; and 11,626.44 MT CO_{2eq}, respectively. Moreover, increase growth in renewables will aid in driving economic growth by reducing imported petroleum consumption. Therefore, Jamaica has an opportunity to take advantage of the chief RE source, solar energy, to aid in the transition to a lower-carbon society as well as improve its energy autonomy.

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