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GEOGRAPHIC INFORMATION SYSTEM-BASED MULTICRITERIA DECISION ANALYSIS OF SOLAR AND WIND POTENTIAL IN JAMAICA

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"For I know the plans I have for you,
declares the Lord, plans to prosper you and not to harm you,
plans to give you hope and a future.
(The Holy Bible, Jeremiah 29: 11)

Resumo

O setor elétrico jamaicano é altamente dependente de combustíveis fósseis importados para sua produção de eletricidade. Essa dependência de importações tem um alto custo, trazendo enormes impactos econômicos e ambientais para o país. O alto preço da eletricidade é uma grande barreira para o desenvolvimento econômico da Jamaica e uma das principais causas de falência de negócios no país. A dependência de combustíveis fósseis para geração de energia também resulta em alta poluição local e custos de saúde e contribui para a mudança climática global. Portanto, há uma necessidade de transição para um sistema elétrico mais sustentável. O governo jamaicano considerou diversificar a matriz elétrica da Jamaica, aumentando as importações de carvão ou gás natural liquefeito (GNL). Embora essas fontes de energia possam fornecer reduções de custo de eletricidade muito necessárias, o potencial de geração de energia renovável merece uma consideração muito maior, pois o país possui um forte potencial de devido à sua localização. Este trabalho envolve um estudo profundo no setor elétrico da Jamaica e indica as melhores seleções de locais para usinas solares e eólicas, tendo em mente as restrições e fatores relacionados a impactos sociais, técnicos, econômicos e ambientais, que devem ser considerados em suas implementações. Assim, foi utilizado um sistema multicritério de apoio à decisão baseado em SIG, utilizado no software Quantum Geographic Information Systems (QGIS) 3.16.9, devido à sua capacidade de armazenar, processar e recuperar informações geográficas, para a realização de resultados do trabalho.

Palavras-chaves: eletricidade. Sistemas de Informação Geográfica (SIG). tomada de decisão multicritério (MCDM). energia solar. energia eólica. seleção de locais apropriados.

Abstract

The Jamaican electrical sector highly depends on imported fossil fuels for its electricity production. This import dependency comes at a high cost, creating enormous economic and environmental impacts for the country. The high price of electricity is a major barrier to Jamaica's economic development and is a leading cause of business failure in the country. The reliance on fossil fuels for power generation results in high local pollution and healthcare costs and contributes to global climate change. As a result of these negative socio-economic factors, there is a need to transition to a more sustainable electrical system.

The Jamaican government has considered diversifying Jamaica's energy mix by increasing coal imports or liquefied natural gas (LNG). Although these energy sources could provide much-needed electricity cost reductions, the potential for renewable energy generation deserves much greater consideration, as the country has strong renewable energy potential due to its location.

This present study offers a dive into Jamaica's current electrical sector and proposes the most suitable site selections for solar and onshore wind power plants, bearing in mind social, technical, economic, and environmental constraints. This study utilizes a multicriteria decision support GIS-based method to achieve the proposed objectives. It proves to be a highly useful technique to systematically deal with rich geographical data and vast areas as well as to manipulate criteria, towards introducing the best sites for solar and wind power plants, further estimating the generating capacity of Jamaica.

Key-words: electricity. Geographic Information Systems (GIS). multicriteria decision making (MCDM). Jamaica solar energy. Jamaica wind energy. site suitability selection.

List of Figures

List of Tables

List of abbreviations and acronyms

AHP	Analytical Hierarchical Process
BOE	Barrels of Oil Equivalent
CO_2	Carbon dioxide
DEM	Digital Elevation Model
EIA	Energy Information Administration (US)
ESSJ	Economic and Social Survey Jamaica
FGA	*Faculdade de Gama*
GEI	Government Electrical Inspectorate
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GPS	Global Positioning System
IAE	International Energy Agency
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
JPS	Jamaica Public Service Limited
LNG	Liquefied natural gas
Ltd.	Limited
MCMA	Multi-criteria decision analysis
MCDM	Multi-criteria decision-making
MSET	The Ministry of Science, Energy and Technology
MSTEM	Ministry of Science, Technology, Energy and Mining
NEP	National Energy Policy
OUR	Office of Utilities Regulation

PIOJ	Planning Institute of Jamaica
PV	photovoltaic
QGIS	Quantum Geographic Information System
SDG	Sustainable Development Goals
TCC2	*Trabalho de Conclusão de Curso 2*
TNC	Third National Communication
UN	United Nations
UnB	*Universidade de Brasília*
UNFCCC	United Nations Framework Convention on Climate Change
UNDP	United Nations Development Programme

List of symbols

A	area
$\circ$	Degree
E	energy
GW	Gigawatt
GWh	Gigawatt-hour
h	hours
km	kilometer
km^2	square kilometer
kV	kilovolts
kWh	kilowatts-h
m	meter
m^2	squared meter
MW	Megawatts
MWh	Megawatts-hour
m/s	meter per second
η	Efficiency
%	Percentage
P	Power
ρ	Density
s	second
US$	United States Dollar
ν	velocity
V	Volts
W	Watt

Contents

1 INTRODUCTION

In this chapter, the justification of this paper is presented, as well as the main objectives of this research project. An introduction of the country, Jamaica, is done as it will establish the basis for the discussion and further add context to the procedures utilized in subsequent chapters of this document.

1.1 Contextualization

Electricity has become a basic necessity of life. It is crucial for poverty alleviation, economic growth, and improving living standards. Due to modernization, the demand for electricity has increased significantly in recent decades. Key sectors of the economy, such as manufacturing, health, construction, entertainment, education, and communication, depend heavily on the generation and supply of electricity for their effective functioning. Unfortunately, Jamaica, like most developing countries, is in the midst of an electricity crisis, due to high oil prices and the inability to rapidly increase its own generating capacity. Recent geo-political occurrences, such as the war in Ukraine, have further highlighted the vulnerabilities of oil-dependent countries and have agitated efforts to diversify domestic energy sources (LIADZE et al., 2022).

Jamaica is located at latitude 18° (north), and longitude -77° (west), with an area of 10,991 km^2 and is the third largest island in the Caribbean. It has a population of 2.993 million people (CRAIG et al., 2020). Its landscape is mainly mountainous, and almost half of the island is more than 330m above sea level. It is divided into three counties and further subdivided into 14 parishes, each having its capitals as seen in figure 1. Often referred to as the *'land of wood and water'*, it is located in the tropical zone, south of the Tropic of Cancer. However, Jamaica's distance north of the equator has a moderating effect on its temperature, and therefore the island is said to have a semi-tropical climate (BUISSERET, 2021).

Due to its location, Jamaica has abundant renewable energy resources, primarily hydro, wind, biomass, and solar. However, this has hardly been tapped in the past and could provide large portions of future energy needs. Only an estimated 10% of Jamaica's total electricity generation ((IRENA, 2021)) is currently obtained from renewable energy sources such as bagasse, hydropower, wind, and solar (IAE, 2019). Jamaica has no notable hydrocarbon reserves and is entirely dependent on imports to meet its oil and coal needs. The country consumes around 60,000 barrels of oil per day (MSET, 2020). Dependence on oil makes the market vulnerable to rising gas prices and exchange rate fluctuations, which directly affect the cost of electricity. Another consequence of its location is its

Figure 1 – Counties of Jamaica.

Source: Elaborated by author, 2022.

vulnerability to destructive weather events. Jamaica and many other Caribbean islands (disaster-prone regions) are prone to serious environmental and safety risks if they use nuclear power.

The high dependency on imported fossil fuels for electricity production is very costly and negatively impacts the economy and environment. It is a major hindrance to Jamaica's economic development and compromises the viability of many businesses in the country. A practical solution for the fuel-related environmental problems faced today is the penetration of renewable energy. In several studies, it has been proven that total greenhouse gas (GHG) emissions exponentially decrease with the implementation of renewable energy systems (BEKUN; ALOLA; SARKODIE, 2019). Promoting the use of renewable energy carries several environmental, economic, and social benefits. Environmental benefits are evident in reducing environmental pollution of air, water, etc.(AKELLA; SAINI; SHARMA, 2009). Using renewable sources also increases the country's self-reliance and regional or national energy independence. Using renewable energy is therefore linked to sustainable development (DINCER, 2000).

In order for the country to have a more sustainable development, it must aim to maximize the use of domestic energy resources and develop the capacity of its energy sector, which requires the use of renewable energy. According to the IEA's World Energy Outlook and other research projects, solar and wind energy have continued to occupy the top spots as the cheapest renewable energy sources. Both energy sources cost significantly less than fossil fuel alternatives and continue to become more affordable every year (IEA, 2021). Jamaica's National Energy Policy 2030 refers to the likelihood that sooner or later, the Jamaican government will need to depend on more renewable energy sources if it is to benefit from clean and less fossil-dependent energy sources.

This study puts forward a strategic methodology that can be applied throughout Jamaica to locate suitable sites for the implantation of new solar and wind energy systems, as they are the cheapest and fastest-growing renewable energy sources. Locating suitable solar and wind energy sites while simultaneously identifying environmentally and geographically favourable locations is a complex decision-making process. Therefore, a GIS-based multicriteria decision method is used to provide a spatial analysis of the country's solar and wind potential.

1.2 Justification

Jamaica will remain vulnerable as long as its energy sector depends on the importation of fossil fuels, because of the high cost of imports, the risk of sudden supply interruptions, and the insecurity of oil market conditions. This challenges the growth of the Jamaican economy greatly and also has negative environmental impacts, causing an increase in the emission of greenhouse gases, further leading to climate change and health problems. Reducing or even eliminating this dependency will have significant impacts on Jamaica's economy and environment. One of the faster and cheaper ways to accomplish this goal is through the use of renewable energy sources, more specifically solar and wind. With the aim of attracting attention to suitable solar and wind sites, this work will point out locations in Jamaica that have the potential for new solar and wind implantation.

1.3 Objective

The main objective of this paper is to locate suitable solar and wind sites for implementing power plants in Jamaica through a Geographic Information System (GIS) based Multi-criteria Decision Analysis, which will provide an estimate of the prospective generating capacity of the country.

1.4 Specific Objectives

- Study the current and future possibilities for the electricity sector in Jamaica;

- Analyze Jamaica using a Geographic Information System (GIS) software;
- Identify and evaluate criteria and factors influencing the exploitation of solar and wind renewable energy sites in the country;
- Generate layers associated with defined criteria and factors in GIS;
- Overlay layers in GIS to create solar and wind suitability maps;
- Identify ideal sites to locate utility-scale wind and solar farms in Jamaica;
- Estimate the capacity of solar and wind energy generation in Jamaica.

1.5 Organization

This work is structured into five (5) main sections. In chapter 1, a brief introduction is made about the country, the objective, and the relevance of the work. In chapter 2, a theoretical background is performed to obtain an understanding of existing studies on the topic. This chapter involves collecting data from websites, reports, and journal articles and selecting the most relevant or up-to-date sources to draw connections between them and make an overall analysis and conclusion. In chapter 4, the methodology used to conduct the research and achieve the main objectives of the work is described, as well as the tools and materials used. chapter 5 presents the discussion and results obtained from the study. Finally, chapter 6 contains the final conclusion of this paper, which summarizes the work done and the final considerations of the author.

2 THEORETICAL BACKGROUND

2.1 Jamaica's Current Energy Profile

Energy represents a fundamental input for modern economies and social life. Jamaica has been almost entirely dependent on imported petroleum as its primary source of energy throughout its modern history, as it currently has no known primary petroleum or coal reserves. In 2020, Jamaica imported approximately $USD273 million in petroleum, becoming the world's 64th largest importer of petroleum. It was also the second most imported product in Jamaica (OEC, 2020).

According to the 2020 Jamaica Energy Statistics, 5,963,625 barrels (approximately 28%) of the total petroleum consumption were contributed to electricity generation (MSET, 2020). The total electricity generated in the same year amounted to 4,227 GWh (JPS, 2020), and as depicted in figure 2, almost 89% of this total was derived from fossil fuels (petroleum and natural gas).

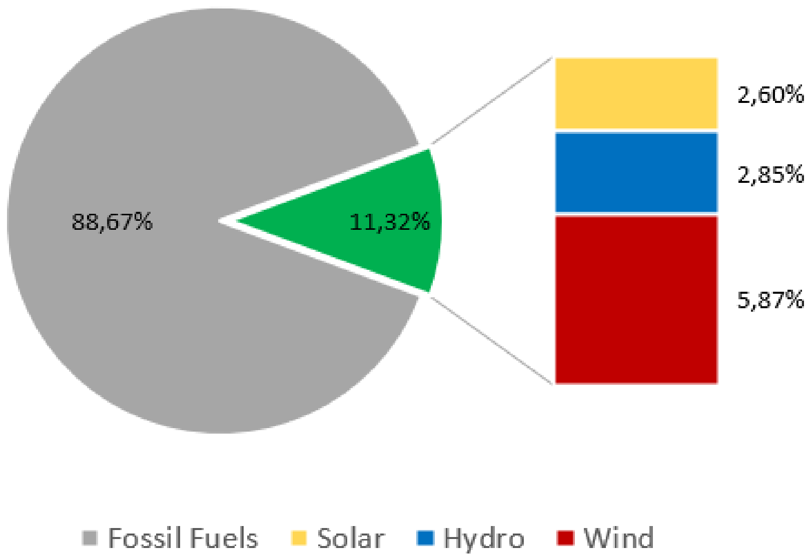


Figure 2 – Electricity Generation by Source in 2020.

Source: Adopted by author (OLADE, 2018).

According to the Third National Communication (TNC) of Jamaica to the United Nations Framework Convention on Climate Change (UNFCCC) in 2018, although Jamaica has a relatively low carbon footprint, for a small country it has a "high per capita GHG emission". TNC forecasts an average increase in the total GHG emissions of approximately one thousand (1000) tonnes of CO_2 every five years in Jamaica between 2015 to 2055 (ROBINSON, 2017).

2.2 Electricity Production

Electricity in Jamaica is supplied by the Jamaica Public Service Company Limited (JPS), the sole electric utility company and distributor in the country. JPS owns and operates four main steam power stations, eight hydroelectric plants, and a wind farm (Munro) (appendix B), and approximately 14000km of transmission and distribution lines which are connected to 54 substations across the island (MSET, 2018). JPS has a 20-year monopoly (until 2027) on the transmission and distribution of electricity in the country through the All-Island Electricity Licence 2001 (MARZOLF, 2014).

In 2020, the available installed generating capacity was approximately 1156 MW, supplied primarily by fossil fuels (83.73%), followed by wind (8.82%), solar (4.93%) and hydropower (2.52%). In figure 3 the installed capacity over the years can be observed, as well as the increase in the capacity of renewable energy.

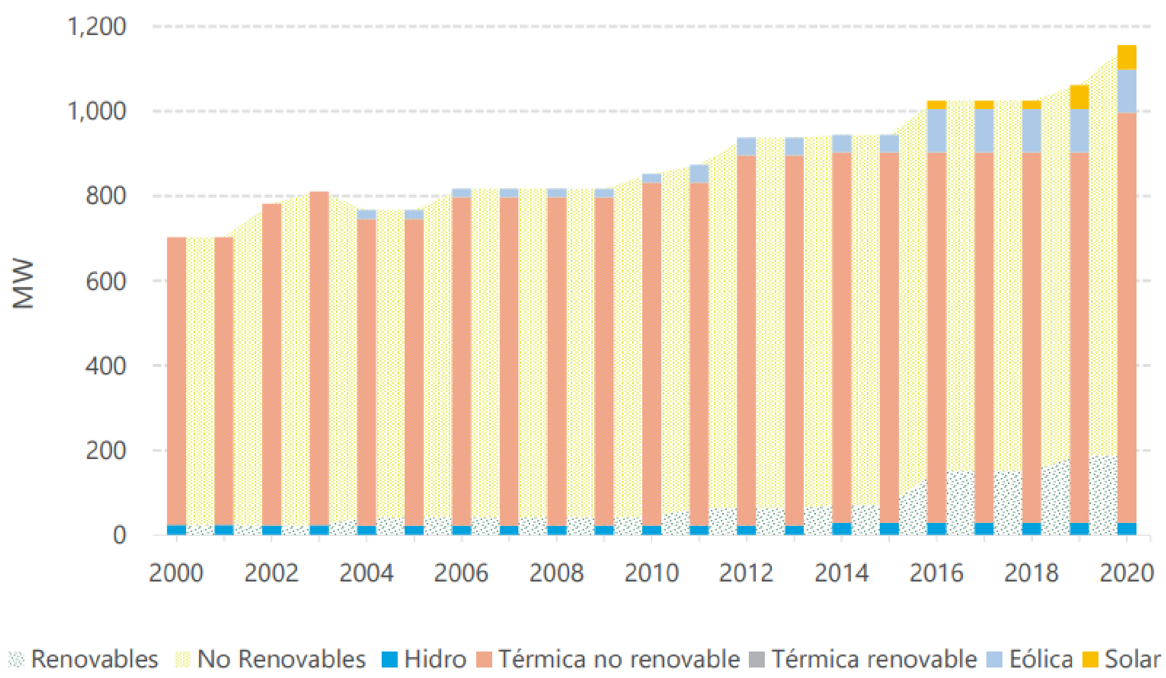


Figure 3 – Installed Capacity of Jamaica.

Source: (OLADE, 2018).

JPS supplies over 60% of this installed capacity, and the remaining are supplied by independent power producers (IPPs).JPS served over 676,879 customers in 2020, of which 100% of the population has access to electricity. The peak demand was recorded to be 638 MW. To date, the highest peak demand that the country experienced was 667 MW (JPS, 2020).

2.3 The Jamaican Electrical Power Grid

Jamaica's total electricity generating capacity can be seen in figure 4. The map of Jamaica's power plants was elaborated from information provided by JPS and the IPPs. In 2020, the Jamaican Electricity Grid achieved a Renewable Energy penetration of 188 MW, or 16.27% of total generating capacity (OLADE, 2018).

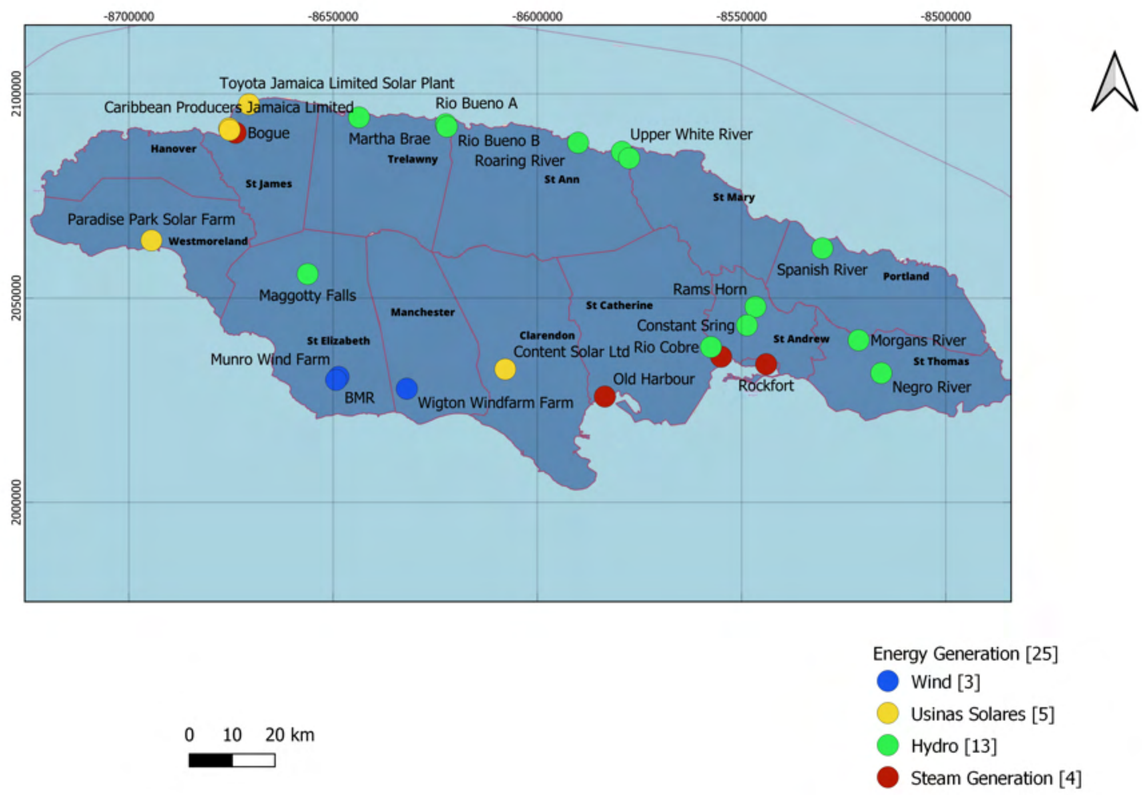


Figure 4 – Electricity Generation of Jamaica.

Source: Elaborated by author, 2023.

In 2015, the OUR released an "Electricity Peak and Energy Demand Forecast 2010 – 2030". In this report, the "Base Value" for net electrical energy demand is projected to grow at an annual rate of 4% over the 2010-2030 period (NATION; SMITH,). Therefore, the installed capacity must grow at the same rate or more to supply the projected demand. Growing the December 2020 installed grid capacity at 4% over the next ten years (to 2030) yields a total required installed capacity of at least 2001 MW. This is shown in the following calculation:

$$
\begin{aligned}
TGC_{30} &= TGC_{20} \times [(1+R)^n] \\
&= 1156MW \times [(1+0.04)^{10}] \\
&= 1711.16MW
\end{aligned} \tag{2.1}
$$

where:

- TGC_{30} is the predicted generating capacity of 2030;
- TGC_{20} is the installed generating capacity in 2020;
- R is the base value for net electrical demand;
- n is the difference between the years.

The penetration target of Jamaica to increase renewable energy to 30% in 2030 must be no less than 600.3 MW (30% of 2002 MW). This also allows us to calculate the minimum annual growth rate of renewable power addition required over 2020 -2030, given the 188 MW of installed renewable capacity as of December 2020. The future value calculation revealed that this minimum value is 9.05%, which is 2.26 times the projected energy demand growth rate (of 4%) over the same period (NATION; SMITH,).

Consequently, over the next 10 years, for every 1kW increase in power demand, a little over 2kW of renewable power must be added to the grid if we are to achieve our 30% target in 2030. It is also evident that if actual growth in energy demand is reduced (through conservation and energy efficiency measures), then a 9.05% annual renewables growth rate could actually yield a penetration level well in excess of 30%, a clear reminder that energy efficiency and conservation measures must be undertaken concurrently with renewable energy integration, to realize the greatest possible gains (NATION; SMITH,).

2.4 Jamaica's Current Renewable Energy Potential

Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed (LOY; COVIELLO, 2005). The most used forms of renewable energy in Jamaica are solar, wind, hydropower, and bagasse. Notable renewable energy generating facilities in Jamaica include 8 hydropower plants, 3 wind farms, and 2 solar farms (recently introduced into the electric power grid in 2016 as shown in figure 3). The total installed capacity from renewable sources mentioned in the previous section was 188MW in 2020. These energy or power plants can be observed in the map elaborated in figure 5; all are grid-connected and positioned along the island's high-voltage transmission lines (138 kV and 69 kV). Table 1 listed each source and their installed potential, however further details on each plant are presented in appendix A.

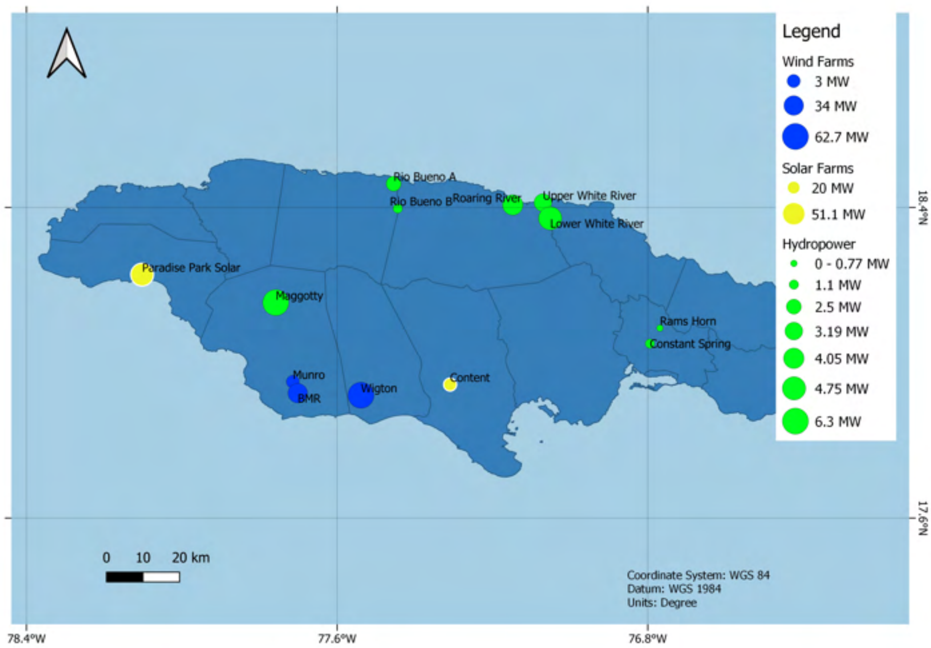


Figure 5 – Renewable Energy Power-plants in Jamaica.

Source: Elaborated by author, 2023.

Table 1 – Installed Capacity of Renewable Energy in Jamaica-2020.

Renewable Source	**Powerplant**	**Capacity [MW]**
Wind	Munro Wind Farm	3,00
Wind	Wigton Windfarm	62.7
Wind	BMR	34
Hydro	Maggotty Falls	6.3
Hydro	Rio Bueno A	2.5
Hydro	Rio Bueno B	1.1
Hydro	Upper White River	3.19
Hydro	Lower White River	4.75
Hydro	Roaring River	4.05
Hydro	Rams Horn	0
Hydro	Constant Sring	0.77
Solar	Paradise Park	51.5
Solar	Content Solar Ltd	20

Source: Elaborated by author based on (JPSCO, 2018).

The increase in renewable energy penetration in the grid shows the improvement of the country's energy mix, which has resulted in environmental and economic benefits. This can be observed in table 2, where the impacts are based on two main factors, the net savings from petroleum imports and the reduction from the emission of CO_2. In 2020 Jamaica experienced a net savings of US$18.8 million, through the avoided cost of imported petroleum, by displacing 335,000 Barrels of Oil Equivalent (BOE) (not including bagasse) representative of approximately 358,360 tonnes of avoidable atmospheric CO_2 emissions.

The emissions from electricity generation vary by type of fuel or energy source, as shown in appendix A and also by type and efficiency of electric power plants. According to the U.S. Energy Information Administration (EIA), CO_2 emissions estimates related to electricity generation from petroleum can be calculated at 1106.77 $g \cdot CO_2e/kWh$.

Table 2 – Renewable energy profile in Jamaica for 2020 based on (OLADE, 2018).

Renewable Source	**Installed Power Consumption Capacity (MWh)**	**Barrels of Oil Equivalent Displaced (‘000 BOE)**	**Avoided Cost (US$ million)**	**Avoided tonnes of carbon dioxide emissions (tCO2)**
Wind	280	174	9.87	309,895
Solar	124	77	4.27	137,240
Hydropower	136	84	4.66	150,521

*Assuming US$55.46/BOE for 2020 (ESSJ, 2021)

*A carbon intensity of 1106.77 gCO2e=kWh is used (EIA, 2021).

Therefore, Jamaica’s current drive towards higher penetration targets of renewable and distributed energy generation is advantageous to its economy through the projected financial savings and positive environmental impacts of avoided carbon dioxide emissions into the atmosphere.

2.5 The Vision of the Jamaican Energy Sector

In 2015, Jamaica, as part of the 193 member states of the United Nations (UN) adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs). This landmark agreement envisions the creation of a better world that is free of poverty and underpinned by universal peace, equity, and inclusion. The SDGs have been integrated into the implementation of Vision 2030 Jamaica - The National Development Plan (NPD).

> "*Vision 2030 Jamaica will create a modern, efficient, diversified, and environmentally sustainable energy sector providing affordable and accessible energy supplies with long-term energy security that contributes to international competitiveness throughout all the productive sectors of the Jamaican economy. By 2030, no less than 20 percent of our energy supply will come from renewable sources.* (JAMAICA., 2009, Pg. 175)

This was revised and the new target for 2030 is 30%. It also states that there should be a 70% diversification among renewable energy sources and greenhouse gas emissions (GHG)reduction of 7.8% (JAMAICA., 2009). As stipulated by the National Energy Policy (NEP), 2009–2030, Jamaica seeks to increase the use of renewable energy in its energy mix, which was further increased to 50% in 2018 by the Prime Minister of Jamaica. This is part of the drive to decrease the use of imported petroleum as fuel, owing to the price volatility and environmental concerns associated with the use of petroleum products in final consumption.

3 GIS-Based Multicriteria Decision Making Method

3.1 Analysis and Decision Making

In order to increase the renewable energy generating potential of a country, it is fundamental to study the possibility, and if so, which energy source is more fitting for a specific location. This, therefore, requires an analysis of the country´s land cover (physical material at the Earth's surface such as rivers, ground, etc.) and use (agricultural, mining, etc.), in order to make decisions on energy type and location.

An analysis is defined as "a detailed examination of anything complex in order to understand its nature or to determine its essential features" (MERRIAM-WEBSTER,). Therefore it can be concluded that it is a question of evaluating an object or something in detail, interpreting each of its parts, and intending to obtain a vision of the whole. Therefore, the act of analyzing is a fundamental part of the process of decision-making.

Decision-making may be reviewed as the process of selecting a course of action from among several alternatives in order to accomplish a desired result. The purpose of decision-making is directly linked to human behaviour and commitment toward a future goal. It involves committing the organization and its resources to a particular choice of course of action thought to be sufficient and capable of achieving some predetermined objective (YADAV, 2020).

In (CONLISK, 1996), it was realized that in complex decision-making processes, decision-making agents fail because they do not have dominant statistical knowledge, make mistakes when updating probabilities based on new information, or even ignore relevant information, not having a rational maximizing behaviour. He concluded that the regularities that are observed, related to the decision-making pattern, cannot be understood using only reasoning alone, but rather from some adopted heuristic. In this way, rationality must somehow be modeled as dynamic adaptation, and then there is a need to use computational models to analyze the decision-making process. The cognitive process of decision-making can perfectly be modeled as a sequence of Cartesian selections based on products (WANG; LIU; RUHE, 2008) consequently, the decision-making process based on algebra (Real-Time Process Algebra - RTPA) arises. Map Algebra, for example, is a recurring process when it comes to Geoprocessing and Remote Sensing, as it refers to a set of operators that manipulate geographic fields (such as images, thematic maps, and numerical terrain models)(BARBOSA et al., 1997).

3.2 GIS-Based Multicriteria Decision Analysis

A Geographical Information System (GIS) is a collection of computational tools comprising of software, database, and spatial information (COELHO, 2009). Such tools are integrated through computational procedures and human resources; through techniques that associate data, allowing and facilitating the analysis, management, or representation of the space and the phenomena that occur in it; aiming at greater ease, security, and agility in human activities related to monitoring, planning, and decision-making related to geographic space. That said, it can provide information to decision-makers, in this case, the focus of this system is mainly operational efficiency. The decision-making process is the essence of administration, and consists of the search and the path to be pursued that is viable, providing the best final result.

Numerous variables have to be considered in decision-making, and the verdict becomes more difficult and complex, demanding evaluation of the criteria, generally representing spatial attributes. In this way, to support decision-making, the Multi-criteria Analysis Methods (MCDA) emerged in the 1960s (ROY; VANDERPOOTEN, 1996).

The MCDA also known as the Multi-criteria Decision Making Method (MCDM), is distinguished by the way in which the criteria and sub-criteria are categorized or hierarchical, in order to allow the combined use of several methods. Most of these procedures use mathematical modeling to harmonize the decision-making process, comparing alternatives or scenarios, with circumspection, and pointing out solutions that are suitable for decision-makers (BELDERRAIN; SILVA, 2005).

In a study done by (NOOROLLAHI et al., 2016), the determination of solar energy sites in Iran, is a difficult and complex process, as it must reconcile social, environmental, technical, and economic parameters. Furthermore, it is subjected to various criteria and regulations. (NOOROLLAHI et al., 2016) combines a MCDM technique (Analytic Hierarchy Process (AHP), which basically multiplies each criterion by an associated weight) with GIS, making it possible to combine eleven (11) criteria (including solar radiation, average annual temperatures, distance from power transmission lines, distance from major roads, distance from residential areas, elevation, slope, land use, average annual cloudy days, average annual humidity and average annual dusty days), dividing them into groups of unsuitable and evaluation criteria. They were evaluated and weighted in the context of the AHP technique in order to establish an order of relative importance. Before applying decision rules in a GIS environment, cartographic information had to be overlaid to integrate all factors into a single layer and quantify the values of each alternative. It is difficult to prioritize multiple and important objectives, therefore GIS techniques (such as buffer zoning, rasters, vectors, and overlap analysis) were applied. The final map classified land suitability for exploiting solar PV farms was prepared using the eleven (11) layers of criteria, by overlay analysis in the GIS environment. Data were classified into six (6) classes within the study area: unsuitable, poor, low, fair, good, and excellent.

This is one of many studies which utilizes the MCDM method in order to make more accurate decisions based on land suitability.

4 MATERIALS AND METHOD

This section explains the methods and materials adopted when collecting and analyzing data for creating solar and wind site suitability maps. The procedures executed for the study can be summarized in figure 6. In the first phase, or the exploratory phase, involves a study of the current Jamaican Electrical Sector and future plans for expanding its capacity through the injection of new renewable energy. It also involves a background study on the GIS-based MCMD methodology applied in similar studies. From these studies, it was possible to adopt criteria and factors for Jamaica.

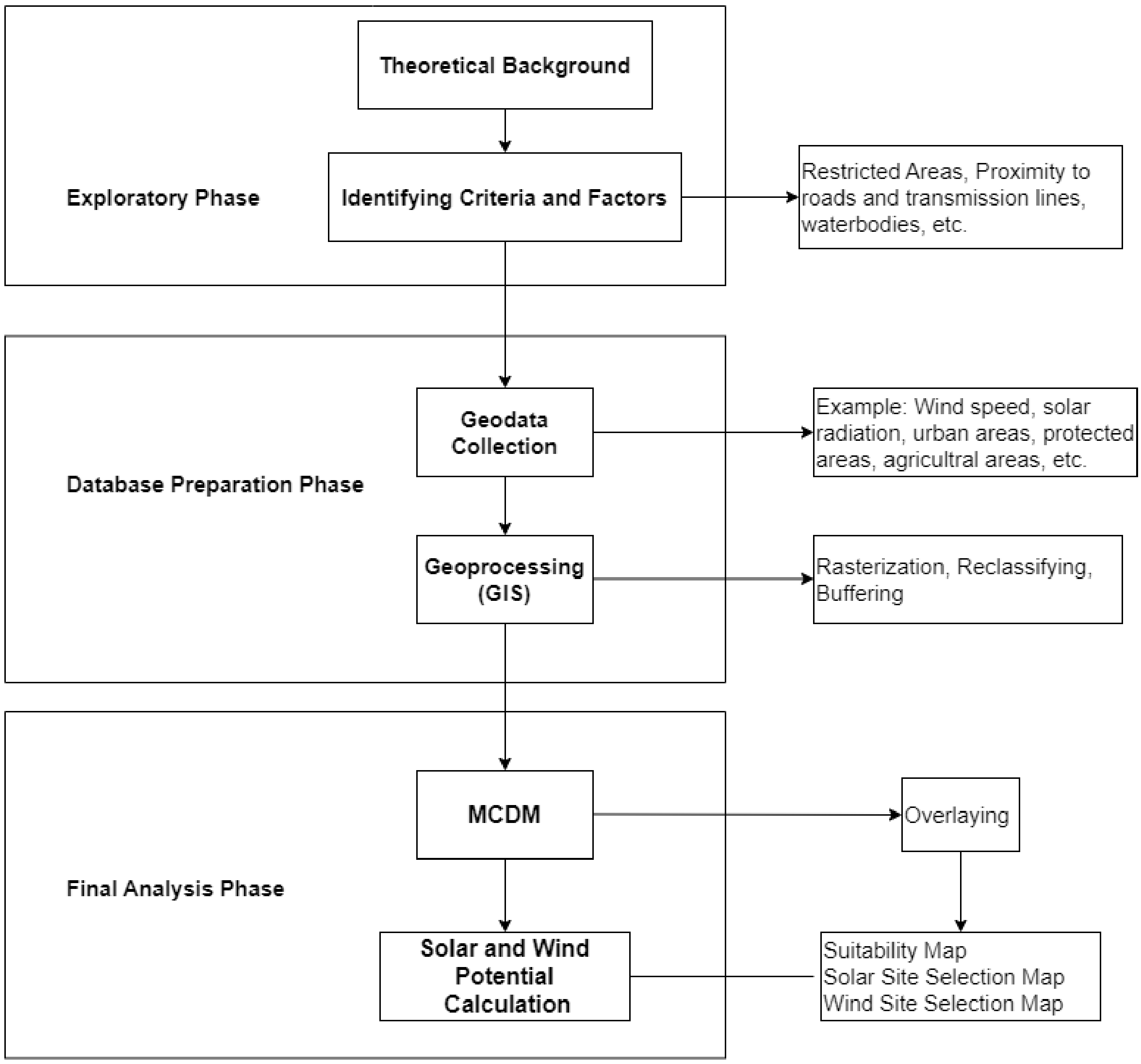


Figure 6 – Methodology Flowchart.

Source: Author, 2023.

4.1 Identifying Criteria and Factors of Solar and Wind Energy Resources

The criteria that influence the siting of solar and wind plants can be classified into several categories: economic, environmental, social, and technical. That is, prior to selecting promising areas, it is necessary to pay attention to current legislation, human (social), and environmental considerations (physical, biotic and anthropic environments). That is, verifying factors that are linked to the geographic location, the socioeconomic disposition of the territorial extension of the study, the biophysical attributes, and the individual interests of the individuals, respecting the environment in which they live.

The current land use and cover are one of the main criteria that affect the location of the installation sites. Land use and cover are deeply connected to human actions on the land, whether due to the need for survival or the search for benefits. Therefore, installation sites should not be proposed in zones that include areas of concentration of water resources, cities, towns, settlements, swamps, lakes, rivers, roads, protected areas, agricultural lands, areas with steep slopes, mining areas, airports, etc. (BREWER et al., 2015). Another key factor is the availability of transport networks (rail and roadways); it is easier to move supplies over the existing transport network as it reduces the cost and potential damage to the environment, caused by creating new networks. An additional economic criterion that must be taken into account is proximity to the energy transfer network (power lines), which is similar to the proximity of the existing transport network (AYDIN; KENTEL; DUZGUN, 2013).

With this knowledge, numerical, vectorial, and geographical data were collected that represent the criterion factors that directly influence the installation of solar and wind power plants, so that they could be utilized in a multi-criteria analysis in the GIS software, QGIS (version 3.16.9).

The factors evaluated according to adoption from various sources are identified in table 3:

Table 3 – Criteria and factor variables in the selection of solar and wind sites.

Criteria	**Factors**	**Buffered Zones**	**Justification**
Economic	Distance to main roads and railways	10km	Building and maintenance of power plants require physical access by road and railway which leads to the sites' main entrances. The road around the perimeter is also necessary for infrastructural development, with internal roads for access to the substation, transmission boxes, and inverters. Conversely, delineated distances need to be applied between all roads in case of accidents from wind turbine malfunction, such as falling debris blades citenoorollahi2016land (AYDIN; KENTEL; DUZGUN, 2013).
	Distance to transmission lines	500m	Nearby proximity of solar and wind farms to the electricity grid is recommended to reduce the cost associated with installing, maintaining and repairing transmission cables (MAKHIJANI et al., 2013).
Environ-mental	Protected Areas	*constraints	It is prohibited by law (NEPA, 2013).
	Urban Areas, towns centers		The distance of the evaluated region in relation to urban centers is a concern of the population, due to the generation of noise and visual impact.
	Waterbodies	200m	Due to technical and financial unfeasibility, the installation should not be carried out in areas of rivers and reservoirs. The only exception is in the case of wind farms, which can be installed in large reservoirs.

Table 3 Continued

Criteria	Factors	Buffered Zones	Justification
Social and safety	Agricultural	*constraints	Restricted zones.
	Airports	*Constraints	It is essential to consider the safe distance from airports to avoid radar signal interpretation (AYDIN; KENTEL; DUZGUN, 2013).
	Mining	*Constraints	Restricted zones.
Technical/ Solar	Slope	Maximum 5°	A solar farm is best placed on flat land with a slope angle between 3 and 10° (Domínguez Bravo et al., 2007). Slope angles <5 degrees were considered feasible.
	Solar irradiation	1300 $[kWhm^2 \cdot year^{-1}]$	The greater the solar potential, the more energy can be generated by these projects.
	Existing Solar Sites		The existing solar farms were subtracted from the areas.

Table 3 Continued

Criteria	Factors	Buffered Zones	Justification
Technical/ Wind	Slope	Maximum 10°	Some wind studies consider slopes as high sloping areas that hinder access to wind farms for installations and maintenance. Subsequently, areas with steep slopes are not considered.
	Elevation	Land area 30m above sea level	The atmospheric boundary layer has wind thresholds affected by topography and land cover. Therefore, Jamaica's topography and land cover are included in the suitability to avoid discontinuity of wind flow and danger zones. The topographic data of the digital elevation model (DEM) utilized was obtained from THE WORLD BANK Data Catalog with Jamaica's digital elevation model raster file comprising digital elevation of 30 m resolution (JAMAICA..., 2021).
	Wind speed	Minimum 6m/s	The greater the wind potential, the more energy can be generated by these projects.
	Existing Wind Sites	170 m times rotor diameter	The wake effects from all existing wind farms are avoided by applying 500 m, that is, the turbulence from the wakes of neighbouring turbines. However, effectively high wind speed may be decreased by wake turbulence intensity due to the closeness of wind turbines, leading to the reduced potential to generate electricity, and where consideration for rotor diameter is given up to 50 km with the recommendation of 170 m times rotor diameter. Consequently, in the case of Jamaica, provisions are made for rotor diameters from 27 m to 112 m since BMR-operated Malvern Wind Farm in Malvern, St. Elizabeth, operates turbines with rotor diameters of 112 m (T., 2018).

Source: Adopted by author, 2023.

4.2 Geodata Collection

After identifying the criteria and factors required to perform the site selection analysis, the geographical information about Jamaica, such as urban areas, protected areas, agricultural areas, mining, water bodies, and also existing solar or wind sites, was gathered. One of the difficulties of this research was finding geographical data on the official government websites of Jamaica, and also recent data. However, based on studies and third-party sources, it was possible to create vector maps by plotting the location information or georeferencing images and also getting access to raster files. The geographic vector (shapefile) and raster (Tagged Image File Format) layers, as well as numerical data, were collected from the following platforms:

- DIVAGIS: Available at: <https://www.diva-gis.org/datadown>. Elevation (raster);
- Global Security: Available at <https://www.globalsecurity.org/military/world/caribbean/jm-maps.htm>. Agriculture and Land Utilization (image);
- Global Solar Atlas: Available at <https://globalsolaratlas.info/download/jamaica>. Solar radiation (raster);
- Global Wind Atlas: <https://globalwindatlas.info/en/area/Jamaica>. Wind speed (raster);
- JCAA- Jamaica Civil Aviation Authority: Available at <https://www.jcaa.gov.jm/index.php/airports-aerodromes/>. Location of airports.
- JPS- Jamaica Public Service: Transmission Lines (image);
- OCHA - The Humanitarian Data Exchange: Available at <https://data.humdata.org/group/jam>. Open Street Map (OSM)(vector), rivers (vector), roads (vector), railways (vector) administrative Boundaries (vector), building (vector).

The data collected from these sources were then used in the software QGIS 3.16.9 to analyze and visualize geospatial data, which will be used to guide decision-support systems for identifying suitable sites by developing a database, based on the factors mentioned in table 3. This is known as geoprocessing.

4.3 Geoprocessing

In this process, GIS tools are used to transform geographic and related data to produce new output datasets as direct results. This study consists of buffering restricted areas by measured distances, then reclassifying rasterized data of boundaries with restrictions, and finally, using rasterized layers to data-mine available land territory. This can be visualized in the flowchart of figure 7.

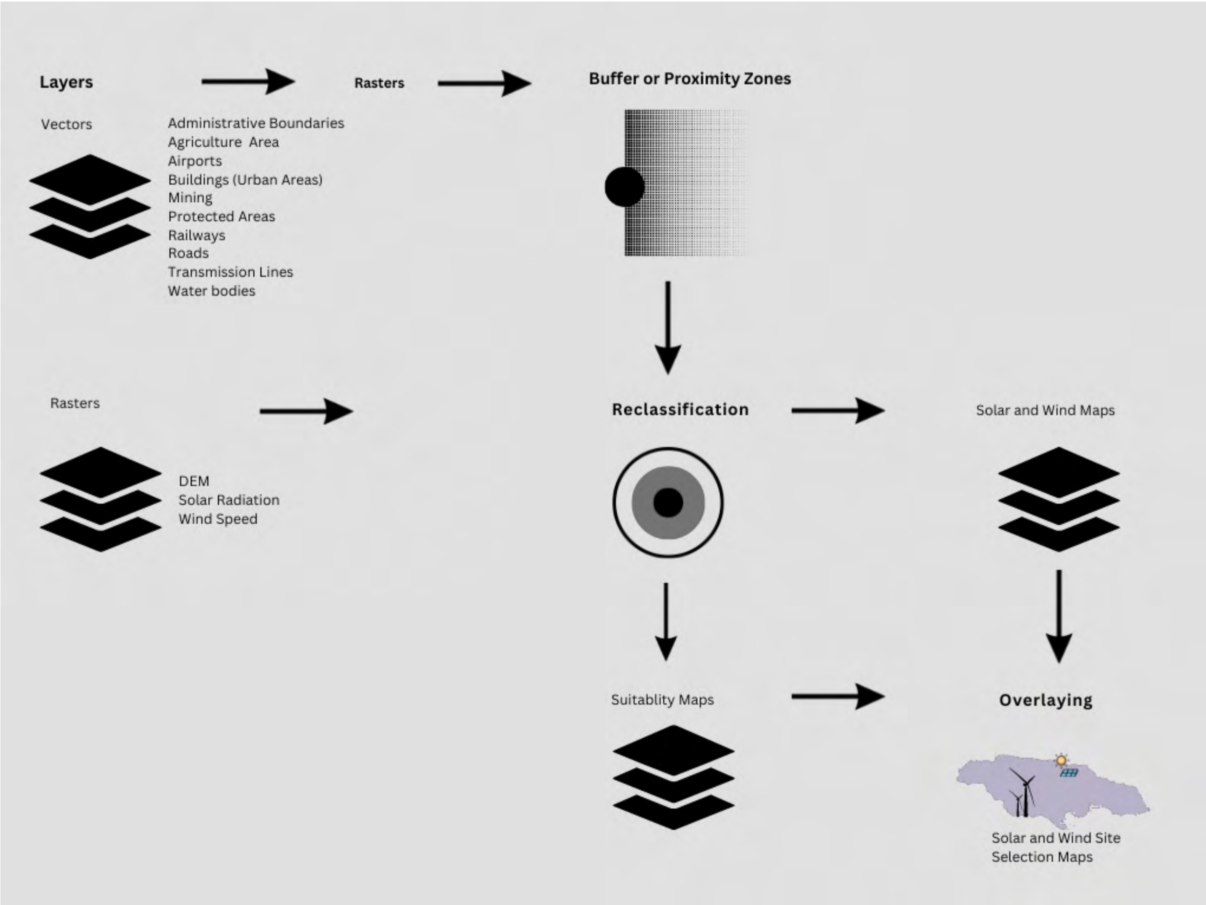


Figure 7 – Flowchart of Geoprocessing.

Source: Author, 2023.

The step-by-step in the geoprocessing stage is as follows:

1. **Add or create layers**: The first step involves adding or creating new layers in the QGIS software, to create a database in which the study is built. These layers may be vectors or rasters;

2. **Rasterize (vector to raster)**: When all the layers necessary for the analysis are available, the second step involves converting all vector geometries (points, lines and polygons) into a raster image. This is done using the *Rasterize* tool. Converting vectors to raster format facilitates the use and calculation of each layer. In this step, the AND logic was used to create raster layers, meaning that:

   - '1' represents constraints (such as protected areas, roads, railways, agricultural, mining, airports, etc.);

- '0' represents No data.

3. **Euclidean Distance**: After the rasterization of the layers, the next step involves creating buffers or proximity maps. This is called Euclidean distance. This is done by using the QGIS tool *Proximity (raster distance)*. The buffer zones in the table 3 were applied to these raster layers. The Euclidean distance indicates the distance from the center of each pixel to the center of the nearest pixel identified as a target pixel. Target pixels are those in the source raster for which the raster pixel value is in the set of target pixel values. The distance ranges were classified according to the buffer zone of each criterion.

4. **Reclassifying**: is done using the *GRASS » r.reclass* and *Raster calculator* tool. Reclassification is a technique that denotes the raster data by changing from single values to new significant values. The tools used to countenance abundant value changes in the contributing raster datasets to the anticipated, quantified, or alternative values. This reclassification grouped the values resulting from the multicriteria analysis into classes from 0% to 100%. The final number of classes depends on the data originating from the mappings, that way, if any of the grids do not have values within any of the defined classes, that class will not be used. In the case of solar, the reclassification 'rule text' was defined as follows (figure 8):

Rule Text	Solar radiation [kWh·m−2] ·year−1]	Wind Speed [m/s]	Rating
1	0 thru 1299	0.9 thru 5.9	Not Suitable
2	1300 thru 1520	6 thru 7.6	Poor
3	1521 thru 1740	7.7 thru 9.3	Suitable
4	1741 thru 1960	9.4 thru 10.9	Good
5	1961 thru 2400	11 thru 14	Excellent

Figure 8 – Reclassifying Rasters.

Source: Author, 2023.

The reclassification of solar irradiation was based on (NOOROLLAHI et al., 2016) study, which states that a PV system requires a minimum average of solar irradiation of 1300 $kWh \cdot m^2$ per year or as 3.5 $KWh \cdot m^2$ per day for economical operations. On the other hand, the reclassification of wind speed is due to a mean interpolated wind speed throughout the data studies of (ENEVOLDSEN; VALENTINE, 2016) and (KRAULAND et al., 2021), with a minimum wind speed of 6m/s was adapted.

5. **Overlaying**: After creating constraints and buffered zones, it is possible to overlay the rasterized layers to create a suitability map. This is done also using the *Raster Calculator* tool. Overlaying the suitable map with the solar raster (solar radiation

and slope) and wind raster (wind, slope, and elevation) created the solar and wind site selection.

4.4 Estimated Solar and Wind Potential

4.4.1 Solar Potential

After the identification of sites suited for solar power, it is possible to estimate the potential solar PV capacity per area (km^2) and in total is W/km^2. In order to calculate this value, first it is necessary to estimate the number of solar modules that are able to fit in the space available as seen in figure 9.

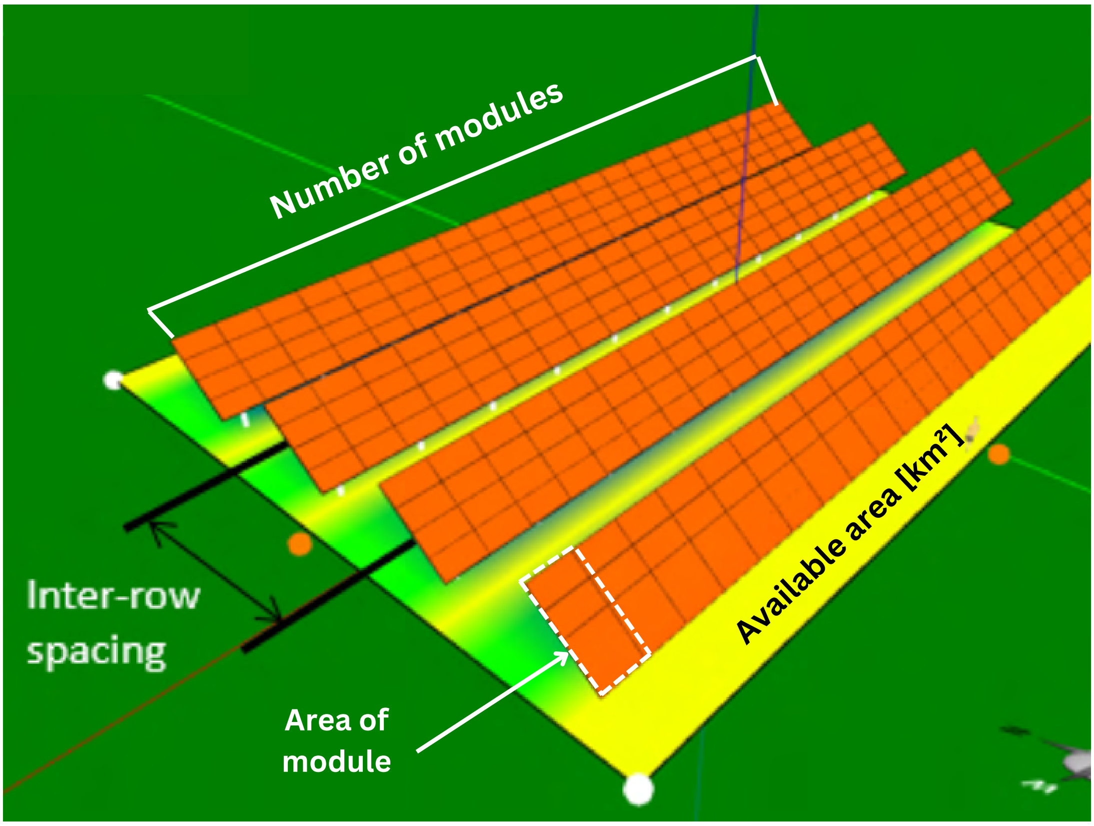


Figure 9 – Layout of Solar Modules in an available area.

Source: Adopted by author, 2023.

- **Area of PV Modules**

Depending on the module technology selected for the PV plant, the total number of PV modules required in the system will vary. The area needed for the implementation of the PV plant will also differ depending on that parameter. The first step involves selecting the module and finding the area of the single module:

$$Area_{module} = length \times height \tag{4.1}$$

- **Row Spacing**

  Tilted or ground-mounted PV systems, require appropriate spacing between each row to avoid accidental shading from the modules that are ahead of each row, which can lead to under-performing systems, or on the contrary, overcompensating, which will lead to a reduction in site potential. The row spacing can be observed in figure 10.

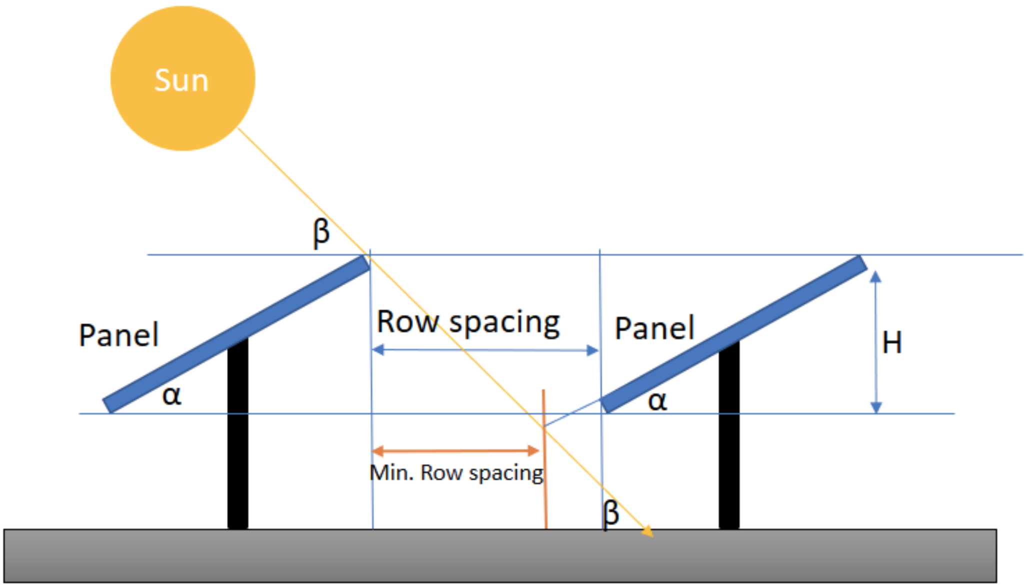


Figure 10 – Spacing between each rows.

Source: (VR, 2021).

Parameters that affect row spacing involve:

- Height difference (H), the back of the module to the surface:

$$H = Panel\, width \times sin(\alpha) \tag{4.2}$$

- Module row spacing:

$$= \frac{Height\, difference}{tan(solar\, elevation\, angle)} \tag{4.3}$$

- Minimum module row spacing:

$$= module\, row\, spacing \times cos(Azimuth\, Correction\, Angle) \tag{4.4}$$

The sun elevation and the Azimuth correction angles can be generated using the software *Sun path chart program* from the University of Oregon (available at <http://solardat.uoregon.edu/SunChartProgram.php>). The data obtained from Jamaica is placed in appendix F.

– Minimum module row spacing area:

$$= minimum\, module\, row\, spacing \times width_{pv}. \tag{4.5}$$

- **Number of modules**

The number of modules that can fit into an available space if found using equation 4.6:

$$Number\, of\, modules = \frac{area\, available}{area\, of\, module + row\, space\, area} \tag{4.6}$$

The total number of modules will then be used to calculate the solar potential of a given area. This is done using equation 4.7.

$$Total\, rated\, power = number\, of\, modules \times rated\, power \tag{4.7}$$

- **Solar Energy**

The estimated electricity generated in the output of the PV system can then be found using equation 4.8 (VASILIţA et al., 2022).

$$E = A \times r \times H \times PR \tag{4.8}$$

where:

– E is Energy (kWh);

– A is the total area of the panel (m^2);

– r is solar panel yield (%);

– H is the annual average solar radiation on tilted panels;

– PR = Performance ratio (coefficient for losses range between 0.5 and 0.9, default value = 0.75).

4.4.2 Wind Potential

- **Number of Wind Turbines and Spacing**

  Wind farms require turbine spacing measurements to reduce or eliminate the wake effect, which results from the changes in wind speed caused by the impact of the turbines on each other. In recent studies, two scenarios with different spacing distances between wind turbines were estimated as seen in figure 11, in which the median minimum is 3.45 times the rotor diameter in meters, and the other, the median maximum is 5.3 times the rotor diameter of selected turbines (ENEVOLDSEN; VALENTINE, 2016) and (ENEVOLDSEN; PERMIEN, 2018). In this case, the spacing between the selected wind turbine types has been estimated as equation 4.9 and equation 4.10, adapted from the work of Enevoldsen and Permien, 2018 (ENEVOLDSEN; PERMIEN, 2018).

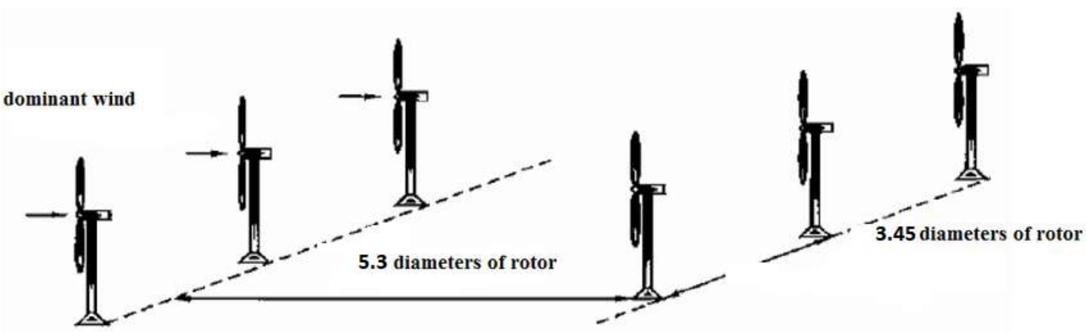


Figure 11 – Recommended turbine spacing to minimize wake effect.

Source: Adopted from (PANAITESCU et al., 2018).

$$A_{min} = \pi * r^2 = \pi * (rotor\,diameter/2 * 3.45)^2 \tag{4.9}$$

$$A_{max} = \pi * r^2 = \pi * (rotor\,diameter/2 * 5.3)^2 \tag{4.10}$$

The area requirements of a single wind turbine are used to determine the potential number of wind turbines for the two scenarios by dividing it from the unrestricted area.

Then, the spacing between each turbine (T_s) is found, using the diameter multiplied by the minimum or maximum value squared as seen in equation 4.11 and equation 4.12:

$$T_{S,min} = (rotordiameter * 3.45)^2 \tag{4.11}$$

$$T_{S,max} = (rotor\, diameter * 5.3)^2 \tag{4.12}$$

The total number of turbines (T_T) for wind energy expansion equals turbine space occupied by one turbine plus recommended spacing between turbines divided into the total unconstrained land area.

$$T_T = \frac{Area\, of\, land\, available\, for\, wind\, installation}{A + T_{s,max}} \tag{4.13}$$

The total rated power or capacity, is found by multiplying the rated power (provided by the manufacturer of the turbine) by the amount of turbines. This will give a brutal estimation of the power capacity available in a certain region .

$$Total\, rated\, power = number\, of\, turbines * rated\, power \tag{4.14}$$

- **Wind Power**

  Wind power or capacity (P) describes the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy of the wind into mechanical energy. This can be found using the following equation:

$$P_w = 0.5 \cdot \rho A v^3 \eta \tag{4.15}$$

  where:

  - ρ = air density (1.225 kg/m^{-3});
  - A = swept area of blades [m^2];

- v = velocity of the wind $[m/s]$;
- η = turbine efficiency [%].

The amount of power generated by a wind turbine however is proportional to wind speed. This is why it is so important to get wind turbines sited in optimal locations with exposure to the strongest winds. This phenomenon can be seen in figure 12. The output power of a wind turbine significantly varies with wind speed and hence every wind turbine has a very unique power performance curve. A power curve aids in wind energy prediction without the technical details of the components of the wind turbine generating system.

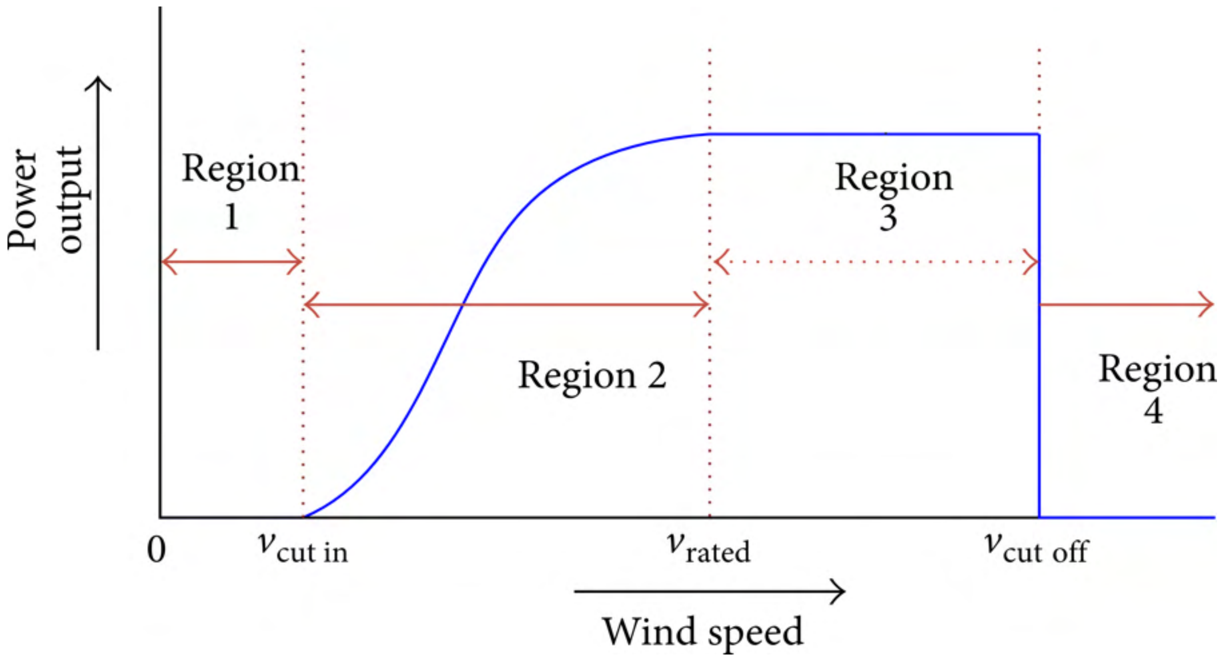


Figure 12 – Typical power curve of a wind turbine.

Source: (SOHONI; GUPTA; NEMA, 2016).

4.5 Data Validation

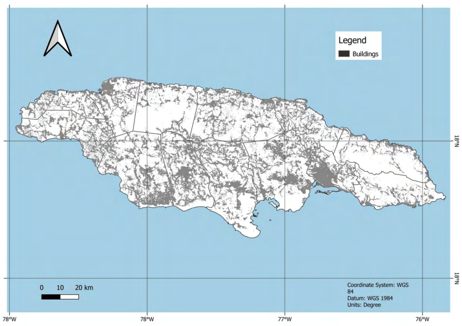
The final step in this methodology involves verifying the results of the study. This is done by comparing the existing power plants with the site selected. It also involves a case study of an existing solar and wind power plant.

5 RESULTS AND DISCUSSION

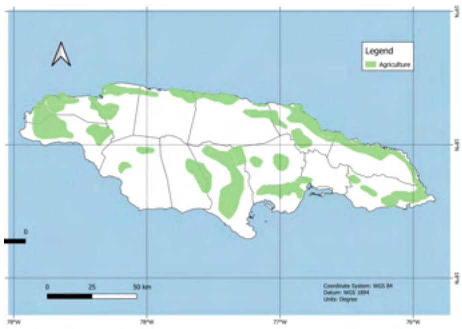
This chapter presents the results obtained from the GIS-based multicriteria analysis of suitable solar and wind sites in Jamaica, and also their potential.

5.1 Restrictive Areas

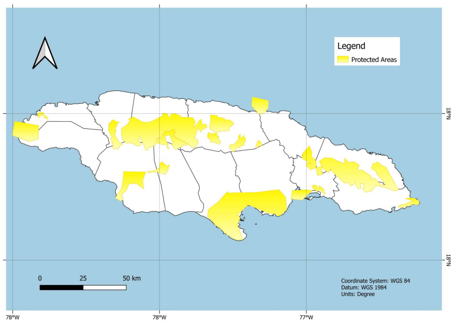
The restrictions analyzed in QGIS are overlaid using the AND logic. According to the results obtained from these layers, unsuitable regions for developing new plants are identified. Some of the defined restricted layers are illustrated in figure 13.



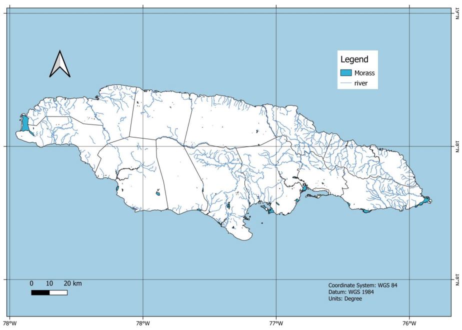
(a) Urban Areas.



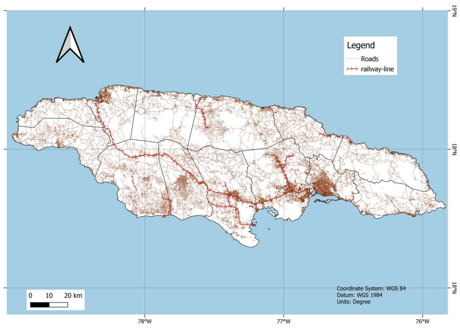
(b) Agricultural Land.



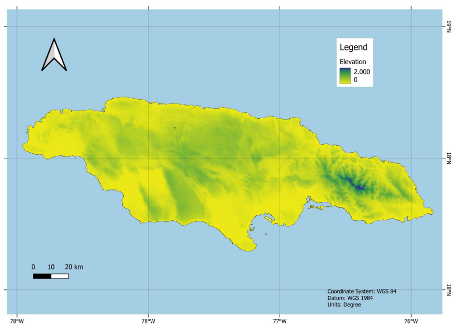
(c) Protected Areas



(d) Wetlands.



(e) Roads and Railways.



(f) DEM 30m above sea level.

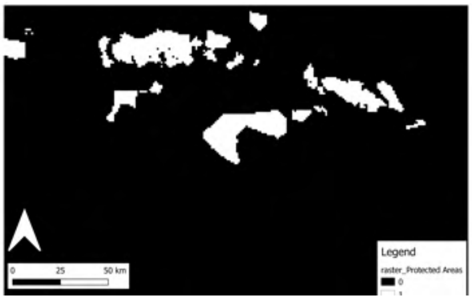
Figure 13 – Restricted areas.

Source: Elaborated by author in QGIS, 2023.

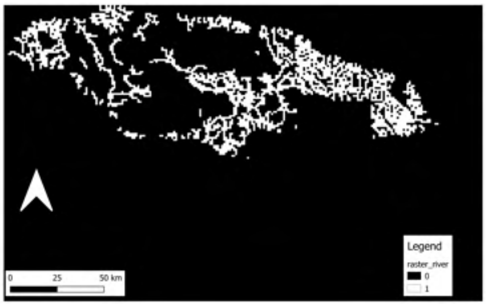
Other constraints that were included, are the existing power plants, mining areas, and airports, but were not possible to see on the map scale used. They were however included in the calculations. Applying the AND logic to the maps mentioned in figure 13, where '1' represents the areas that are unavailable and '0' represents no data, it was possible to generate the following rasterized layers in figure 14.

(a) Rasterized Urban Areas.

(b) Rasterized Agricultural Land



(c) Rasterized Protected Areas



(d) Raterized Wetlands

(e) Rasterized Roads and Railways

Figure 14 – Rasterized Areas.

Source: Elaborated by author in QGIS, 2023.

These new layers represent the permanently restricted zones. After which, it was necessary to create Euclidean distance (buffer zones) mentioned in table 3. The buffer zones however are more flexible and could be adjusted based on the study area. The buffer zones in the criteria table were used to create new layers. One example can be observed in figure 15, of the Jamaican power line grid. The colour scale surrounding the power line represents the distance from the actual line to the distance mentioned in table 3.

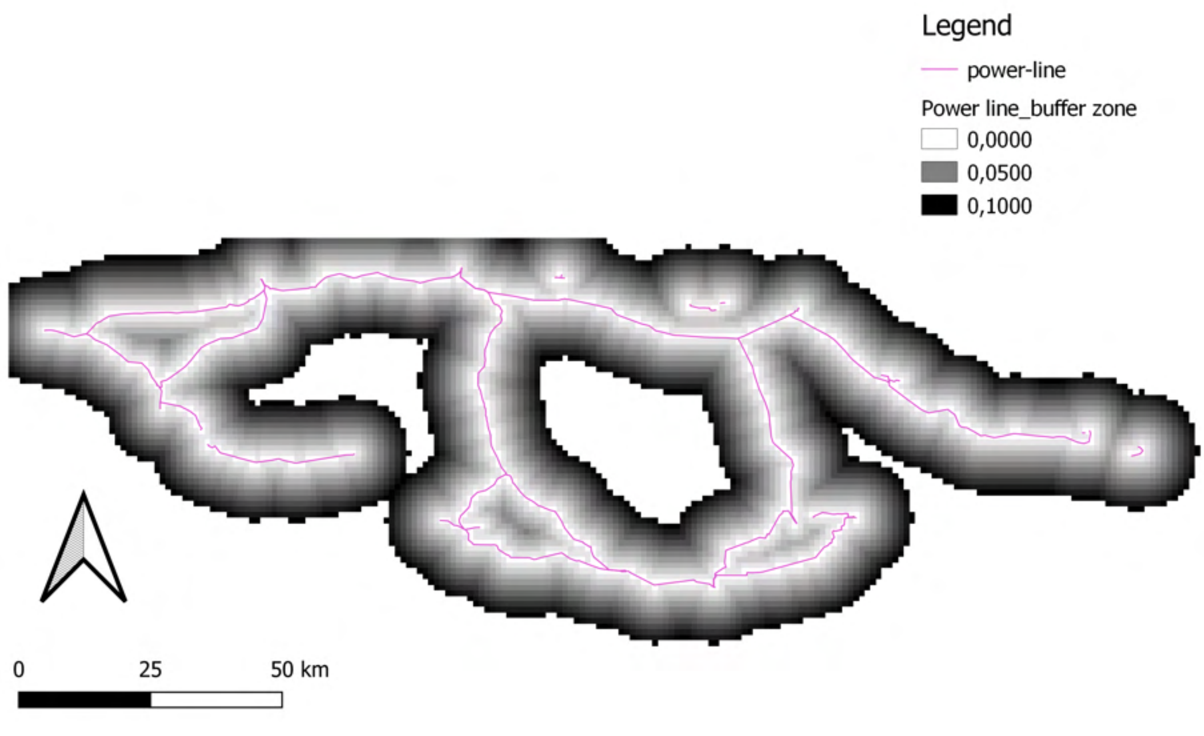


Figure 15 – Transmission Buffer Zone.

Source: Elaborated by author, 2023.

The constraints and buffered zones are then calculated as shown in figure 16, in order to create the final suitability map of figure 17.

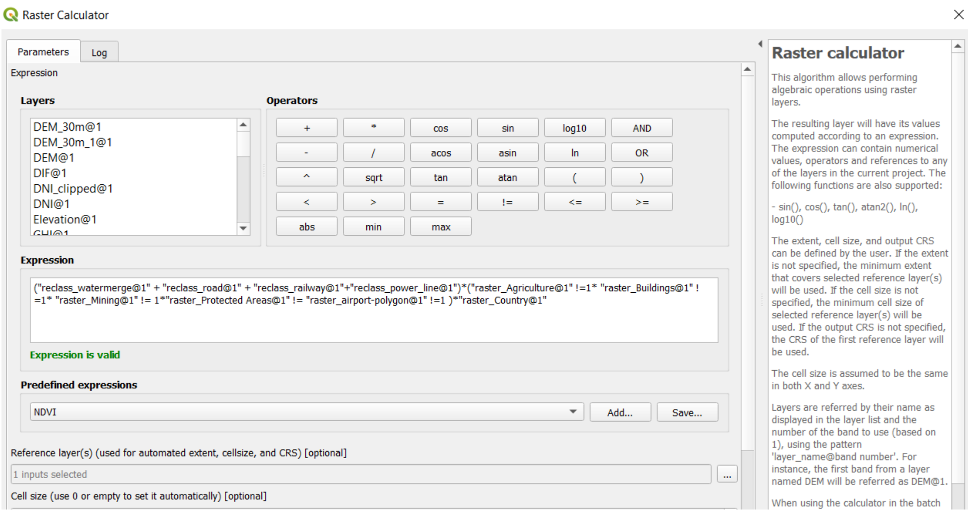


Figure 16 – Raster Calculator.

Source: Adopted from QGIS, 2023.

Green represents the zones suitable for site selections (1) and white represents the unsuitable zones (0).

This new raster layer was used to generate a report in the QGIS software in order

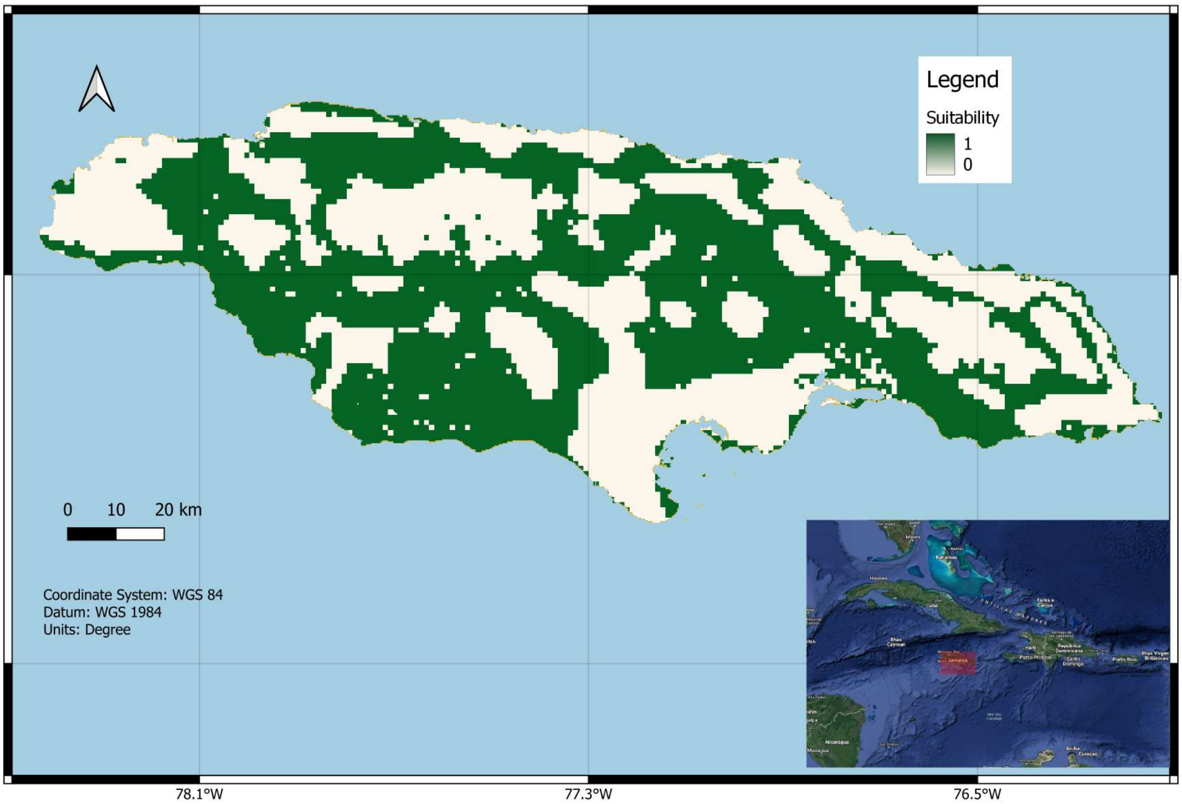


Figure 17 – Suitability Map.

Source: Elaborated by author in QGIS, 2023.

to find the area of each pixel which makes up the map. From the raster 46.5% or 5,106.57 km^2 (see appendix D), the island, is unsuitable for the implantation of solar or wind farms.

5.2 Solar Site Selection and Estimated Potential

- **Solar Site Selection**

  The solar site selection map involved the overlaying of the solar specifications (solar irradiation, slope, and elevation maps) with the suitability map. Using the reclassification system in figure 8, the solar site suitability map was generated and shown in figure 18. The area of the solar site can be seen in section E.2, in which the value of '1' represents the unsuitable sites (5134.1 km^2), therefore leaving 5,856.9 km^2 area (over 50% of the island) suitable for solar implementation.

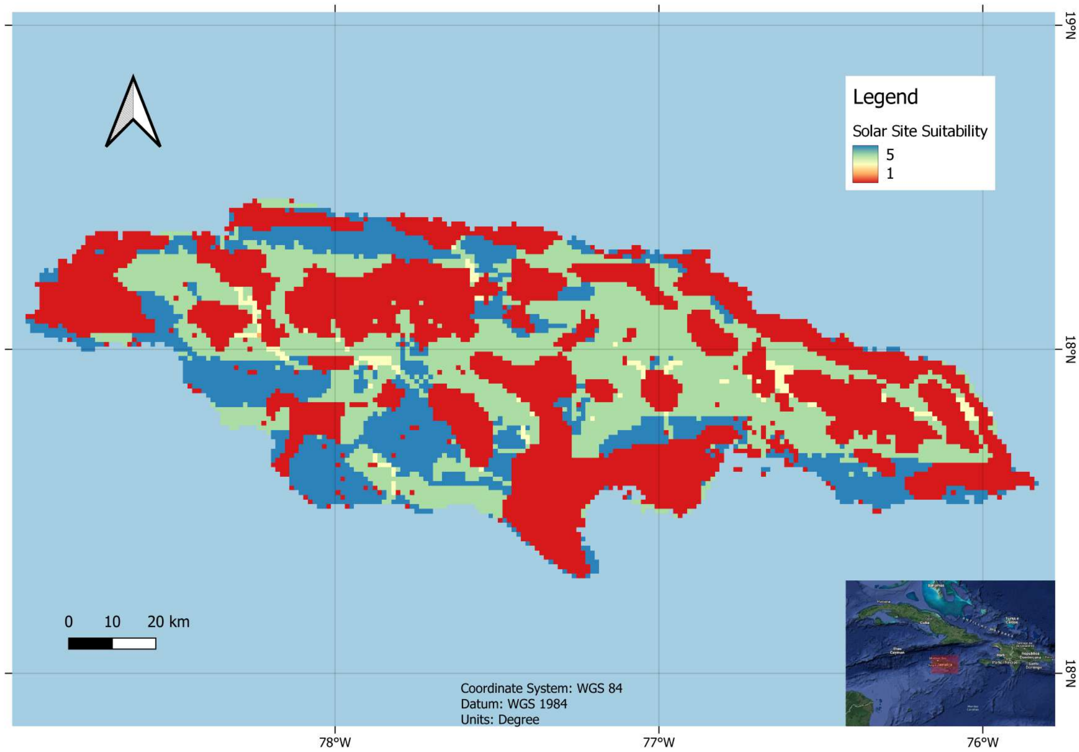


Figure 18 – Solar Site Selection Map.

Source: Elaborated by author in QGIS, 2023.

- **Solar Power Estimation**

  From the report generated in QGIS, the 'class 5' zones or the area of 'excellent' solar sites (the blue areas in figure 18 represent 2241,97 km^2, approximately 20% of the island. Adopting the *Canadian Solar HiKu7 PERC- 650W* model solar panel to facilitate the calculations, the following specifications were gathered:

  - Module power: 650 W;
  - Dimension of the module: 2.384 by 1.303 by 0.035m;
  - Area of the module: 3.11 m^2;
  - Height difference ($\alpha = 30°$): 1.192m
  - Module row spacing ($\beta = 30°$): 2.065m (appendix F);
  - Minimum module row spacing = 1.534m (appendix F);
  - Area of module spacing = 2m^2.

  The tilt angle (α) of the solar panel was estimated to be 30°. In appendix F, a time interval from 9 AM to 3 PM window during the winter solstice for the worst case scenario. From this, the sun elevation (β) was found to be 30° and the Azimuth angle is found by creating two vertical reference lines down from each time reference. The difference between south going in either direction turns out to be 42º and is used to determine the minimum module Row spacing. Using the solar site selection map (figure 18), 'class 5' or 'excellent' area, the theoretical number of *Canadian Solar HiKu7 PERC- 650W* modules that could fit is 438,741,683.

$$Number of modules = \frac{2241.97km^2}{3.11m^2 \times 10^{-6} + (2m^2) \times 10^{-6}} = 438,741,683\,modules.$$

$$\begin{aligned} Installed\,capacity &= 438,741,683 \times 650W \\ &= 2.85182 \times 10^{11}W \end{aligned}$$

From the rated power of a single module, the total capacity or rated power is estimated at 285.18 GW. This value is a rough estimate and does not include the efficiencies, and areas of storage for inverters, number of panels in series or parallel, batteries, and other components of a solar farm. Table 4 shows the class of solar radiation and its areas.

Table 4 – Solar Site Suitability Classification.

Solar Power Class		Solar Radiation $[kWh/m^2]$ (yearly average)	Land Area $[km^2]$
1	Not suitable	<1300	-
2	Poor	1300 to 1520	1.17
3	Suitable	1521 to 1740	171
4	Good	1741 to 1960	3454.63
5	Excellent	1961 to 2400	2241.97
		Total:	**5868.77** km^2

Source: Author, 2023.

The estimated electricity generated from the *Canadian Solar HiKu7 PERC- 650W* based on equation 4.8, with an annual solar average of 1300 kWh/m^2 (worst case scenario) and area of modules ($number of module \times area of a single module$) is found to be:

$$\begin{aligned} E &= (438,741,683 \times 3.11\,m^2) \times .209 \times 1300\,kWh/m^2 \times 0.75 \\ &= 2.78 \times 10^{11}kWh \\ &= 278000\,GWh\,(annually) \end{aligned}$$

For an annual electricity generation of 278000GWh of solar energy, the average peak sun hours have to be approximately 2.6 h per day or 975h per year.

5.3 Wind Site Selection and Estimated Potential

- Wind Site Selection

  The applications to the solar site selection were also made for the wind site selection, however replacing the solar specifications with those of the wind (such as wind speed, land elevation, and slope). This can be represented in figure 19. The area found for the site selection of wind plants is 32541,75 km^2, which can be observed from the report in section E.3.

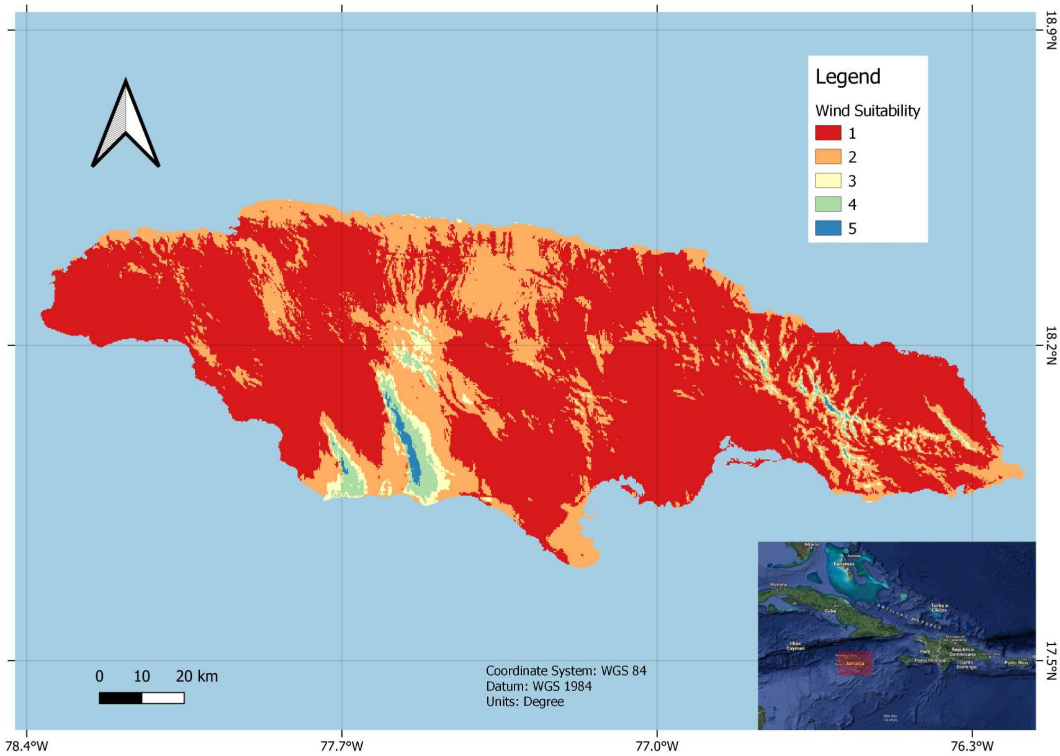


Figure 19 – Wind Site Selection Map.

Source: Elaborated by author in QGIS, 2023.

In figure 19, it can be observed that the southwest side of the country has the most suitable site selection areas (blue areas). From the QGIS tool *r.report*, it was possible to calculate the area of each pixel that makes up each class (from the reclassification step). Those pixels that fall under 'class 1' (red), were the areas with wind speed less than 6m/s or with restrictions or both. From the raster report, which can be seen in section E.3, the island has approximately 3254.18 km^2 of land suitable for the implantation of wind energy. This represents 29.6% of the total country. In table 5, the classes and their area can be observed.

- **Wind Power Estimation**

  For the estimation of wind power, the wind turbine data from the BMR-Malvern Wind Farm, mentioned in table 3 is used as a reference, to estimate the wind capacity

Table 5 – Wind Site Suitability Classification.

Wind Power Class		Wind Speed [m/s]	Land Area [km^2]
1	Not suitable	<6	-
2	Poor	6 to 7.6	2763.98
3	Suitable	7.7 to 9.3	171
4	Good	9.4 to 10.9	198.31
5	Excellent	11 to 14	44.32
		Total	**3254.18** km^2

Source: Author, 2023.

available in the country. BMR wind farm currently has 11 wind turbines with a rotor diameter of 112 m and rated power of 3300 kW each, using the maximum spacing value (5.3). Consequently, the turbine area and its spacing (T_S) are determined below.

$$A = \pi * (\frac{diameter}{2} * 5.3)^2 = 276743.4171m^2 = 0.2767km^2$$

$$T_{s,max} = (112m * 5.3)^2 = 352360.96m^2 = 0.3524km^2$$

After finding the area of the single turbine and the maximum spacing between the turbines, it is possible to estimate the number of turbines that will be appropriate for a certain area. Using the wind site selection map (figure 19) of Jamaica with the 'class 5' or 'excellent' classification, the number of turbines is found to be:

$$T_T = \frac{44.32km^2}{0.2767km^2 + 0.3524km^2}$$
$$= 70\, wind\, turbines;$$

Theoretically, approximately 70 Vesta V112- 3.3 MW wind turbines can be placed, which converts to a potential capacity of approximately 231MW. This capacity does not include the wake effect and other losses. The same calculations can be made for the site selection in the 'class 2' to 'class 4' zones. According to figure 12, the power output however will be proportional to the wind speed.

Using the wind speed 6 m/s for an average of 5 hours daily, with an efficiency rating of 30% (as wind turbines tend to be 20% to 40% efficient at converting wind into energy (JUSTINO; CLEMENTE, 2020)), the generating electricity potential is therefore found to be:

$$
\begin{aligned}
P = 0.5 \times 1.225\, kgm^{-3} \times 9852m^2 \times *(6m/s)^3 \times .30 \\
= 391.025kW
\end{aligned}
$$

$$
\begin{aligned}
E = P \times t \\
= 391.025\, kW * 5h \\
= 1955.13\, kWh
\end{aligned}
$$

5.4 Data Validation Results

This section compares the existing solar and wind power plants that are currently in Jamaica, to the methodology adopted by this study to test its validity. Using the solar and wind site maps obtained in the study results, it is possible to observe in 21 and 20.

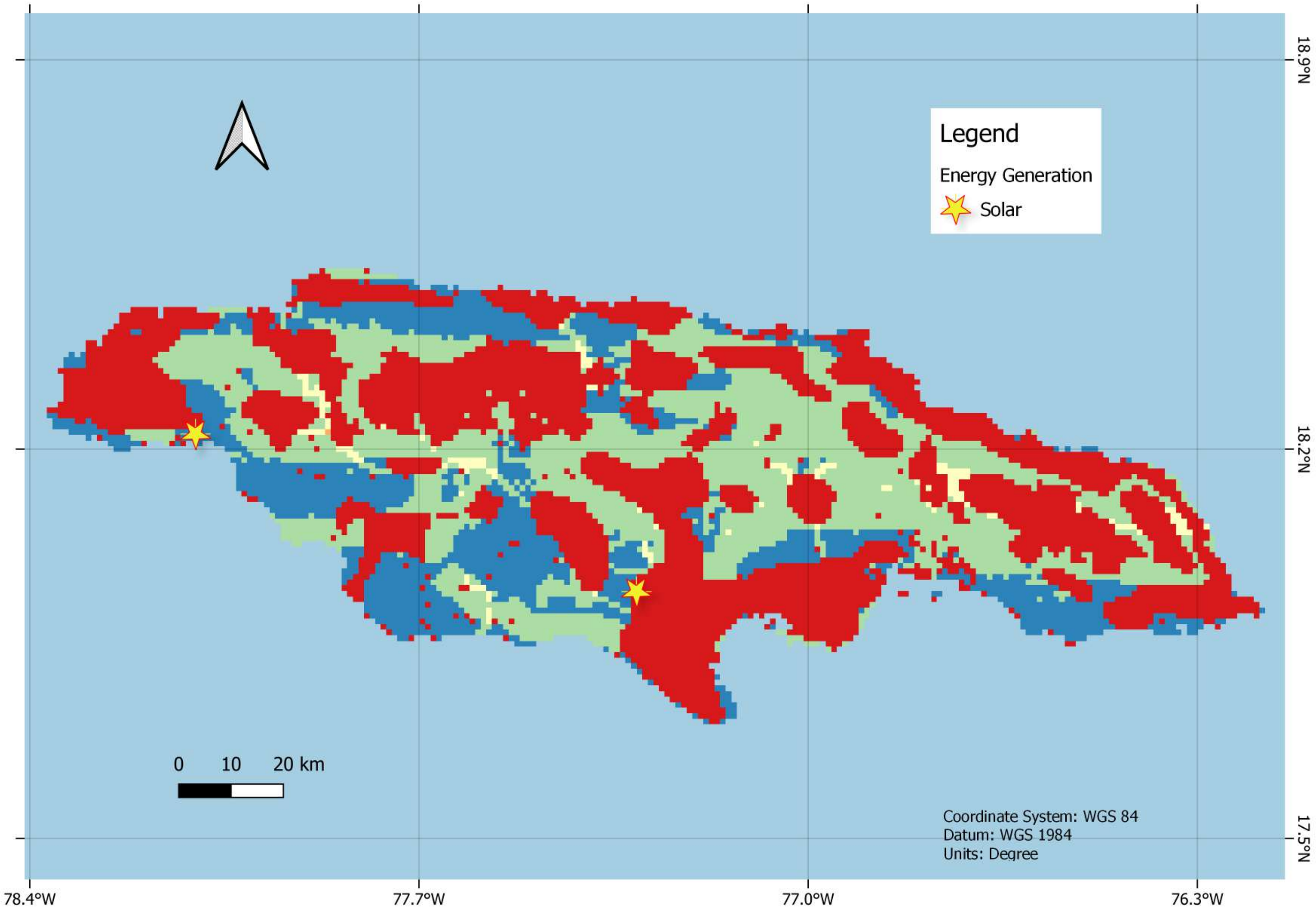


Figure 20 – Solar Site Validation.

Source: Elaborated by author in QGIS, 2023.

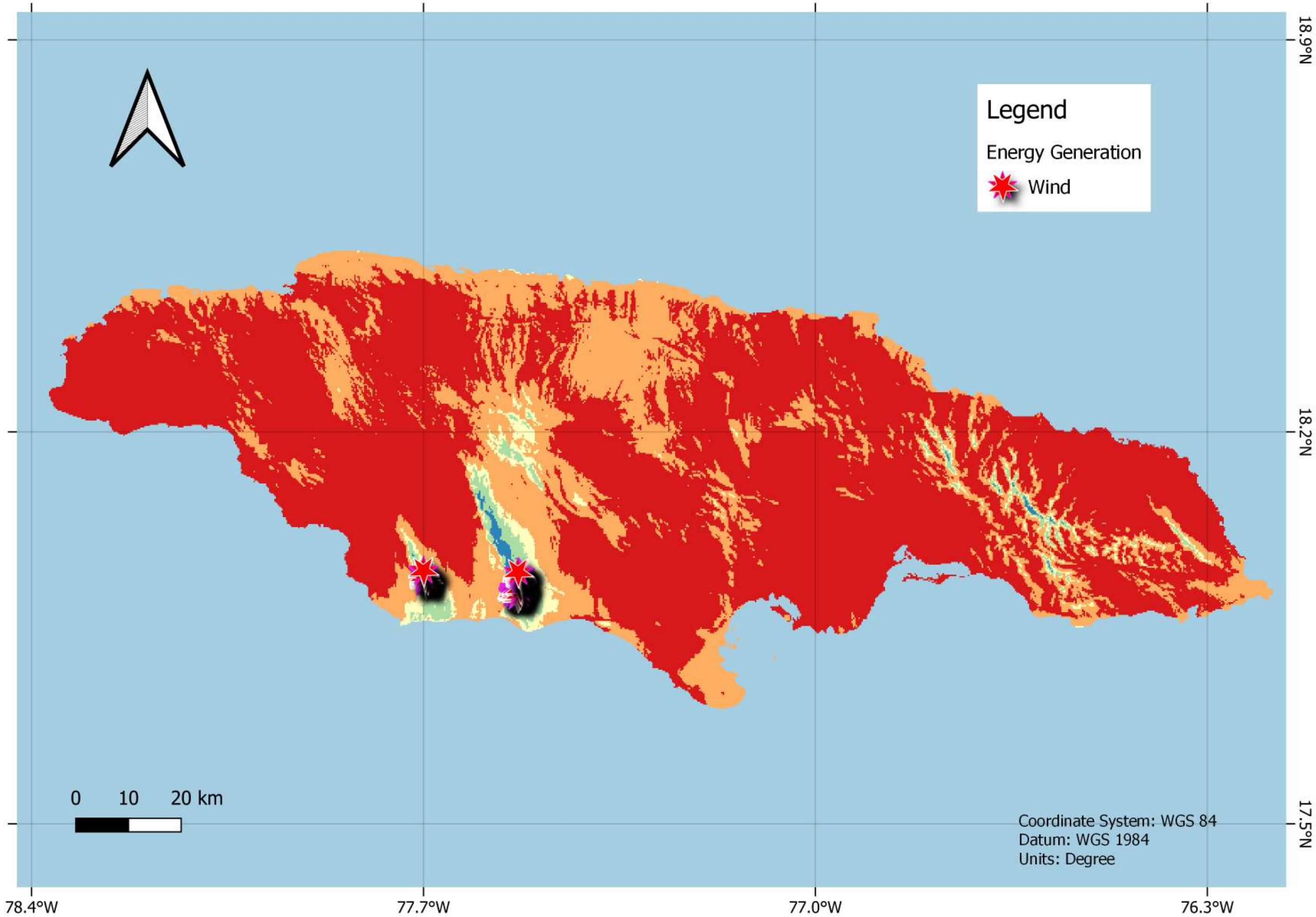


Figure 21 – Wind Site Validation.

Source: Elaborated by author in QGIS, 2023.

5.4.1 Content Solar Farm

Content Solar Farm, one of the 2 current utility-scale solar farms in Jamaica is located at 17.941 N, 77.308 ° W, Clarendon, Jamaica. From figure 20, it is possible to observe that the power plant is situated in a 'class 5' zone (excellent). The calculations performed to estimate the solar capacity of Jamaica can also be applied to this area. Figure 22 takes a closer look at the power plant.

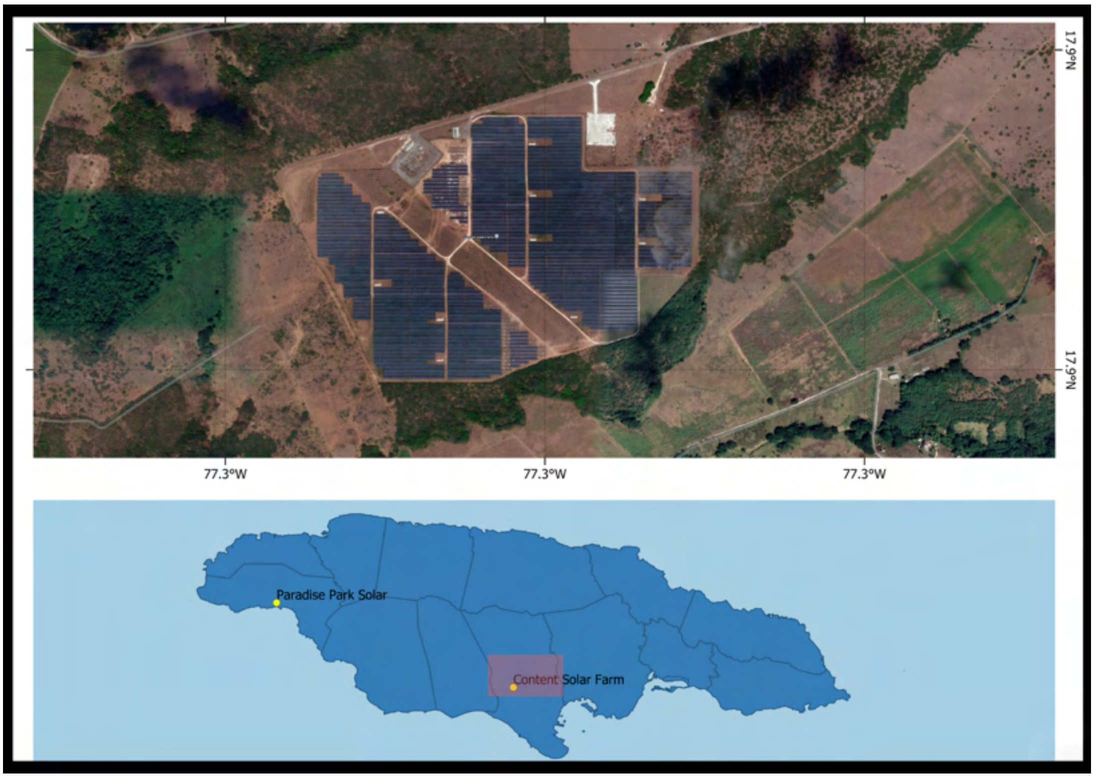


Figure 22 – Content Solar Jamaica.

Source: Elaborated by author in QGIS, 2023.

The following information was obtained from (WRB, 2017) about the Content Solar Farm:

- Capacity: 20 MW;
- Generated Electricity per day: 170 MWh;
- Area utilized: 160 Acres (0.647497 km^2);
- Number of modules: 91,200;

The information that was not provided included:

- Types of solar modules;

- Dimension of modules;
- Rated Power;
- Row spacing;
- Tilt angle.

Using the prevision calculations and assuming the tilt angle and row spacing to be equivalent, it can be estimated the following:

- Area of module:

$$\begin{aligned} Area\,of\,module &= \frac{area\,available}{Number\,of\,modules} - row\,space\,area \\ &= \frac{0.647497km^2}{91,200} - (2 \times 10^{-6})km^2 \\ &= 5.1 \times 10^{-6}m^2 \end{aligned}$$

- Rated Power:

$$\begin{aligned} Rated\,power &= capacity \div number\,of\,modules \\ &= \frac{20 \times 10^6 W}{91,200} \\ &= 219W \end{aligned}$$

- Generation time [hours]:

$$\begin{aligned} Time &= Electricity\,generation \div capacity \\ &= \frac{170MWh}{20MW} \\ &= 8.5\,hours\,per\,day \end{aligned}$$

5.4.2 BMR Wind Farm

The BMR Wind Farm located at 17.923 N,-77.687 W, in St. Elizabeth, currently consists of 11 Vesta V112-3.3MW turbines and is adjacent to the existing JPS Munro Wind Farm. Its capacity is 36MW and is situated in the 'class 5' (or excellent) zone in figure 21. The area of the project site of each turbine is 0.352 km^2, which is conclusive to the calculations done in this study. The turbines can be observed in figure 23. The power plants generate approximately 120,000 MWh of energy per year (POWELL, 2021).

$$\begin{aligned} Time &= Electricity\,generation \div capacity \\ &= \frac{120,000MWh}{36MW} \\ &= 3333.3\,hours\,per\,year \end{aligned}$$

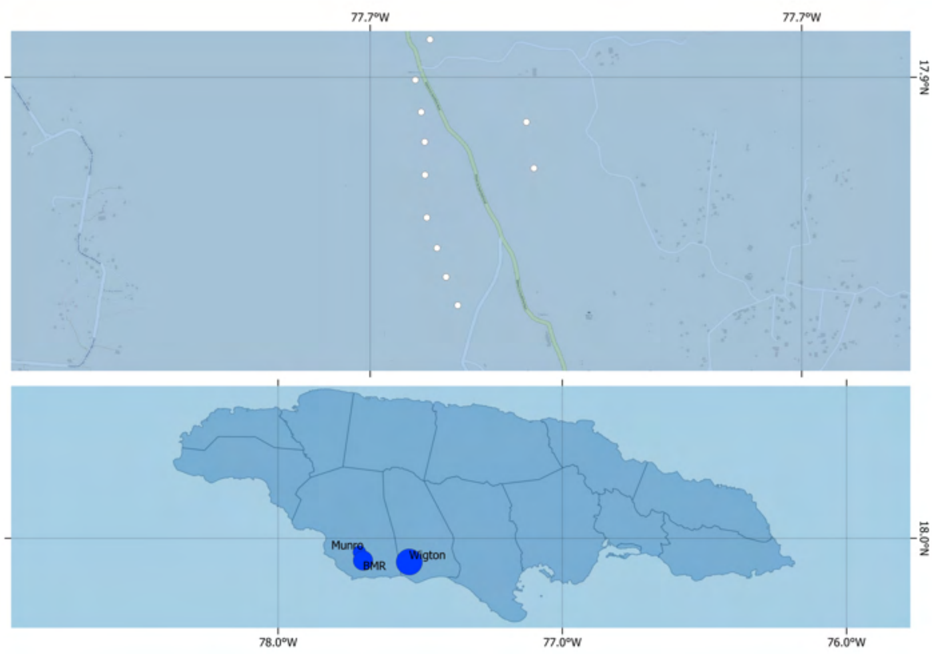


Figure 23 – BMR Windfarm

Source: Elaborated by author in QGIS, 2023.

Using the QGIS tool *measure*, the estimated spacing between each turbine is shown in figure 24. The spacing between each wind turbine was less than those used in the calculations. With an average spacing distance of 177,67m, the turbine spacing was estimated at 1.5 times the rotor diameter. This may be due to the number of turbines. Fewer turbines will have a smaller wake effect and therefore it is possible to reduce the spacing distance.

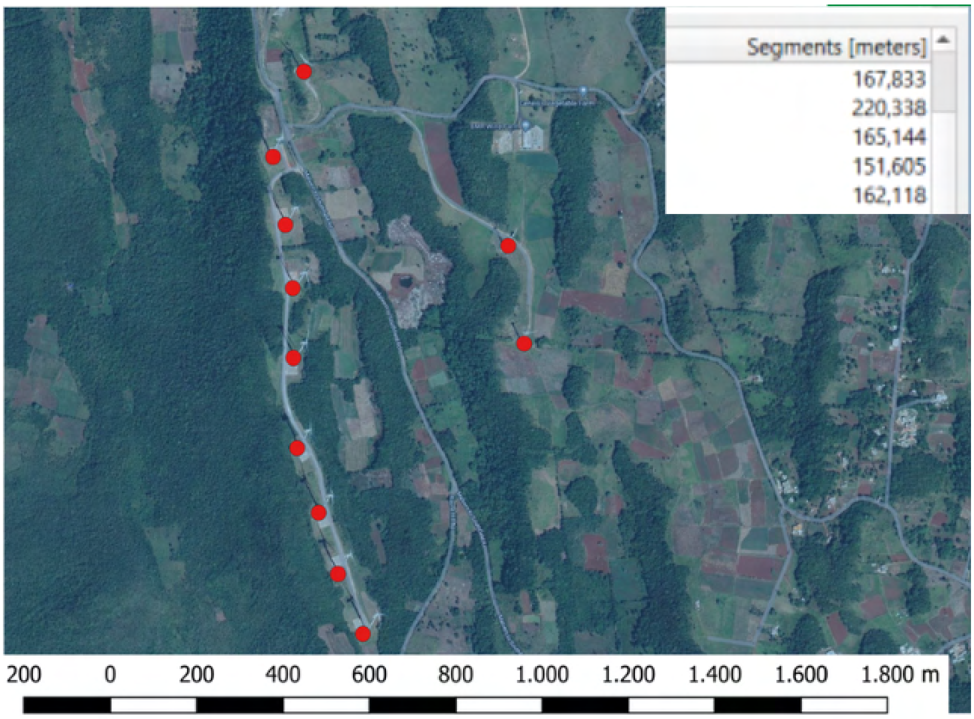


Figure 24 – Spacing of BMR Wind Turbines

Source: Elaborated by author in QGIS, 2023.

6 CONCLUSION

As a developing country, the need for energy continues to grow, leaving Jamaica to find more sustainable ways to increase its generating potential. Extensive utilization of fossil fuel has led Jamaica to a vulnerable economy and also a less sustainable environment, as the pollutants continue to increase. The solution proven to decrease these problems is through the increase of renewable energy resources, due to their characteristics such as availability, pollution reduction, and, more importantly, sustainable development.

This study provides a GIS-based multicriteria analysis, which identifies the economic, social, technical, and environmental criteria and factors involved in the selection of suitable solar and wind sites while eliminating unforeseen eventualities related to intrusion on areas of environmental significance, mainly protected regions and places deemed ill-suited. These criteria were then used to generate restricted and buffered layers, providing a suitability map. This was then analyzed using solar and wind specifications in order to find suitable sites for their implementations. The methodology of this study can provide information to investors, policymakers, and energy planners, who may have an interest in Jamaican sustainable development.

Taking these criteria into consideration and discovering the most suitable sites for solar and wind, the suitability maps were then used to estimate the solar and wind capacity of the island, respectively. The penetration of this potential power will lead to a decrease in CO_2 emissions in the atmosphere and also a decrease in the country's importation of fossil fuels, further leading to a stronger and more independent economy.

The estimation of solar and wind capacity faced a number of limitations. This study does not address the importance of local perceptions and the acceptance of solar or wind farm expansion, and neither does it have onsite measurements using pyranometers (solar radiation) or anemometers (wind speed) devices known to reduce uncertainties and eliminate bias. The method compensates for shortfalls in this study by assessing the comparative importance of several variables utilized as factors and criteria when making complex decisions. This study also disregarded parameters such as the land area needed for the battery, inverter, and other important components of the system storage. It also disregarded the wind potential of offshore wind sites.

Finally, it is noted that the objectives proposed for the study were fully met. The use of the GIS was proven to be fundamental in the selection of solar and wind sites, and also the calculations of the energy potentials.

6.1 Suggestions for Future Work

This study has limitations as the calculations made were based on a superficial level. It is of great importance to measure the solar and wind energy potential of the region studied using equipment indicated for this purpose. Only with this measurement would it be possible to correctly dimension the systems and have a real value. Daily weather conditions such as air density, storms, and other environmental factors were not taken into consideration. In wind turbines, power output is related to the local air density, which is a function of altitude, pressure, and temperature. Dense air exerts more pressure on the rotors, which results in higher power output. Jamaica is also a storm-prone region. Which could affect variables such as wind speed and solar irradiation. The inclusion of these variables will provide future studies with closer approximations.

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Appendix

Appendix A – Population Density of Jamaica

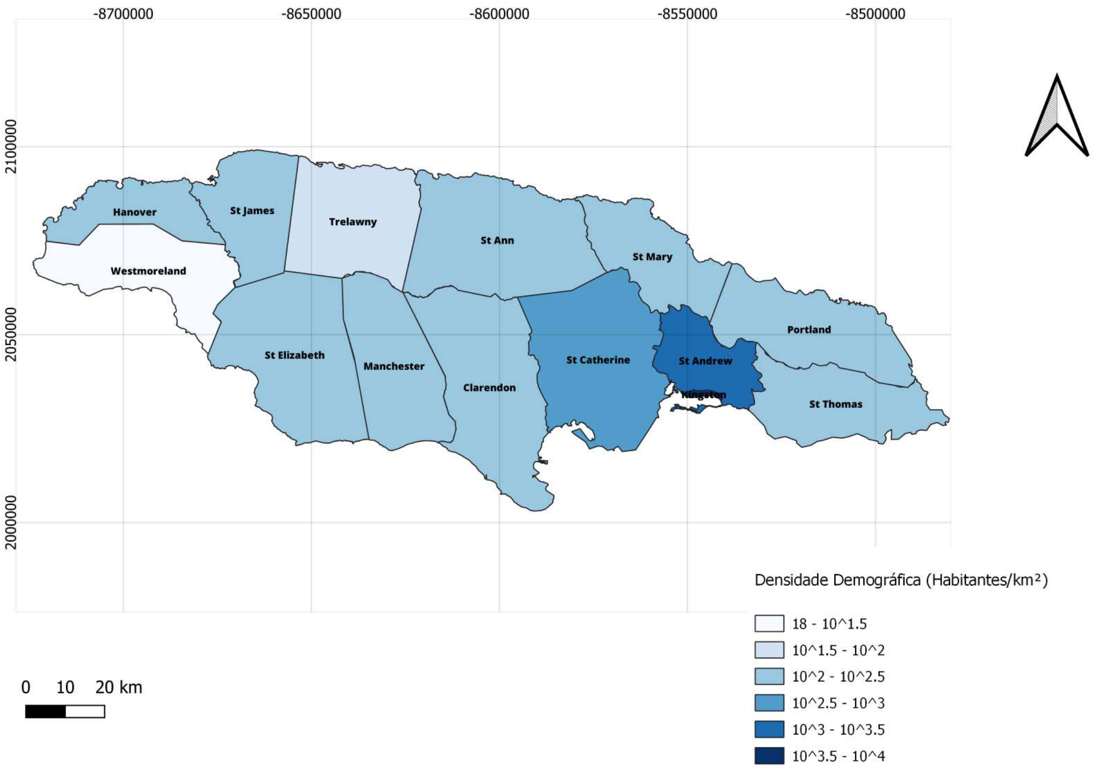

Figure 25 – Population Density Map of Jamaica (2021).

id	Parish (Freguesia)	Capitais	População	Área (km²)	County	Densidade (Habitante/km²)
1	St Elizabeth	Black River	150993	1210,7	Cornwall	124,715
2	Westmoreland	Savanna-la-mar	144817	7852	Cornwall	18,443
3	Kingston	Kingston	90544	22,7	Surrey	3988,722
4	St Catherine	Spanish Town	518325	1190,6	Middlesex	435,348
5	St Andrew	Half Way Tree	573369	434,5	Surrey	1319,606
6	Manchester	Mandeville	191720	827,8	Middlesex	231,602
7	Hanover	Lucea	72519	450,8	Cornwall	160,867
8	St James	Montego Bay	184662	591,2	Cornwall	312,351
9	St Thomas	Morant Bay	94410	742,2	Surrey	127,203
10	Portland	Port Antonio	82183	813,9	Surrey	100,974
11	St Mary	Port Maria	114227	611,3	Middlesex	186,859
12	Clarendon	May pen	246322	1192,9	Middlesex	206,49
13	Trelawny	Falmouth	75558	874,3	Cornwall	86,421
14	St Ann	St Ann's Bay	173323	1210,25	Middlesex	143,213

Figure 26 – Population Density of Jamaica (2021).

Appendix B – Notable Energy Generating Plants in Jamaica

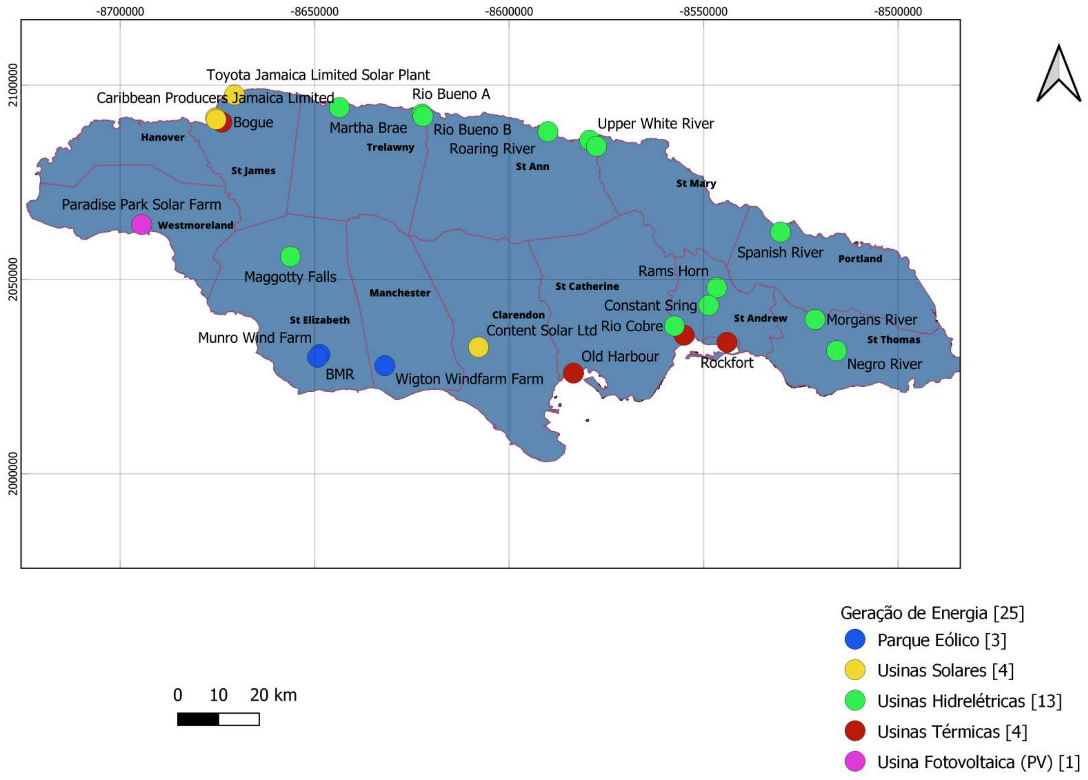

Figure 27 – Notable Energy Generating Plants in Jamaica Map.

Generation Type	Phase	Agents	Power Plant	Capacity (MW)	Expansion Plan (MW)
Wind	Active	JPS	Munro Wind Farm	3,00	
Wind	Active	Wigton Windfarm Limited	Wigton Windfarm Farm	62,7	
Wind	Active	JPS	BMR	34	
Solar	Active	Neoen	Paradise Park Solar Farm	51,5	
Hydro	Active	JPS	Maggotty Falls	6,3	7,2
Hydro	Active	JPS	Rio Bueno A	2,5	
Hydro	Active	JPS	Rio Bueno B	1,1	
Hydro	Active	JPS	Upper White River	3,19	
Hydro	Active	JPS	Lower White River	4,75	
Hydro	Active	JPS	Roaring River	4,05	
Hydro	Desactivated	JPS	Rams Horn	0	
Hydro	Active	JPS	Constant Sring	0,77	
Hydro	In construction	Studio Pietrangeli	Negro River	2,3	
Hydro	In construction	Studio Pietrangeli	Morgans River	2,7	
Hydro	In construction	Studio Pietrangeli	Spanish River	7,8	
Hydro	In construction	Studio Pietrangeli	Rio Cobre	1,5	
Hydro	In construction	Studio Pietrangeli	Martha Brae	4,4	
Hydro	Studied		Great River		8
Hydro	Studied		Green River		1,4
Hydro	Studied		Laughlands Great River		2
Hydro	Studied		Wild Cane River		2,5
Hydro	Studied		Yallahs River		2,6
Hydro	Studied		Back Rio Grande		28
Solar	Active	WRB Energy Company	Content Solar Ltd	20	
Solar	Active	Caribbean Producers Jamaica Limited	Caribbean Producers Jamaica Limited	0,45	
Solar	Active	Rainforest Seafoods	Rainforest Seafoods Solar Plant	0,33	
Solar	Active	Toyota Jamaica Limited	Toyota Jamaica Limited Solar Plant	0,17	
Thermoelectric	Active	JPS	Rockfort	40	
Thermoelectric	Active	JPS	Hunts Bay	54	
Thermoelectric	Desactivated	JPS	Old Harbour	0	
Thermoelectric	Active	JPS	Bogue	211,5	

Figure 28 – Notable Energy Generating Plants in Jamaica.

Appendix C – Area Calculations

C.1 Area of Jamaica

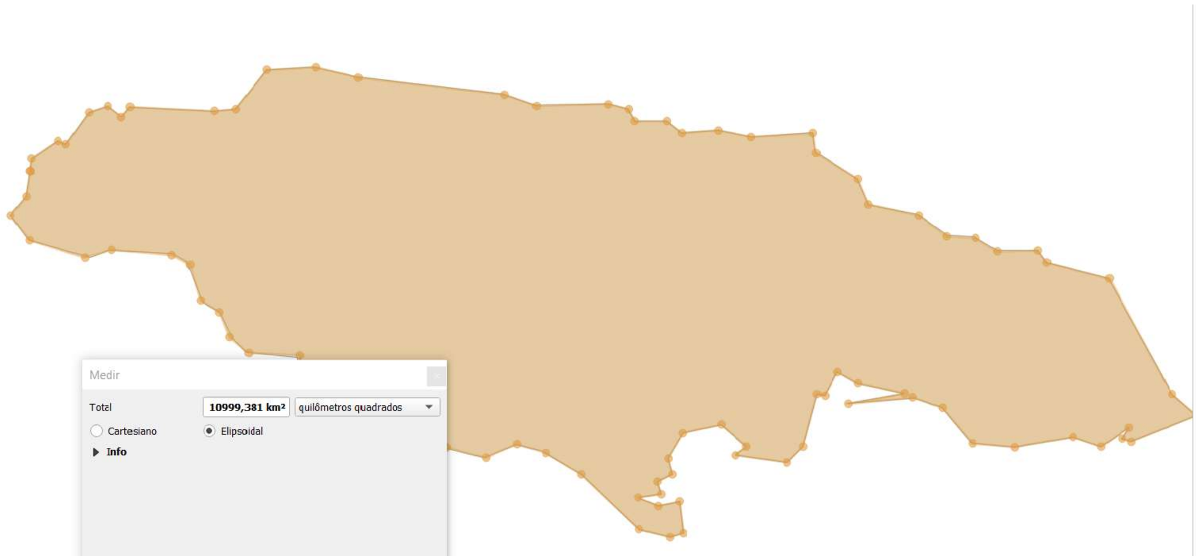

Figure 29 – Evaluation of the Area of Jamaica.

C.2 Transmission Line- 138kV

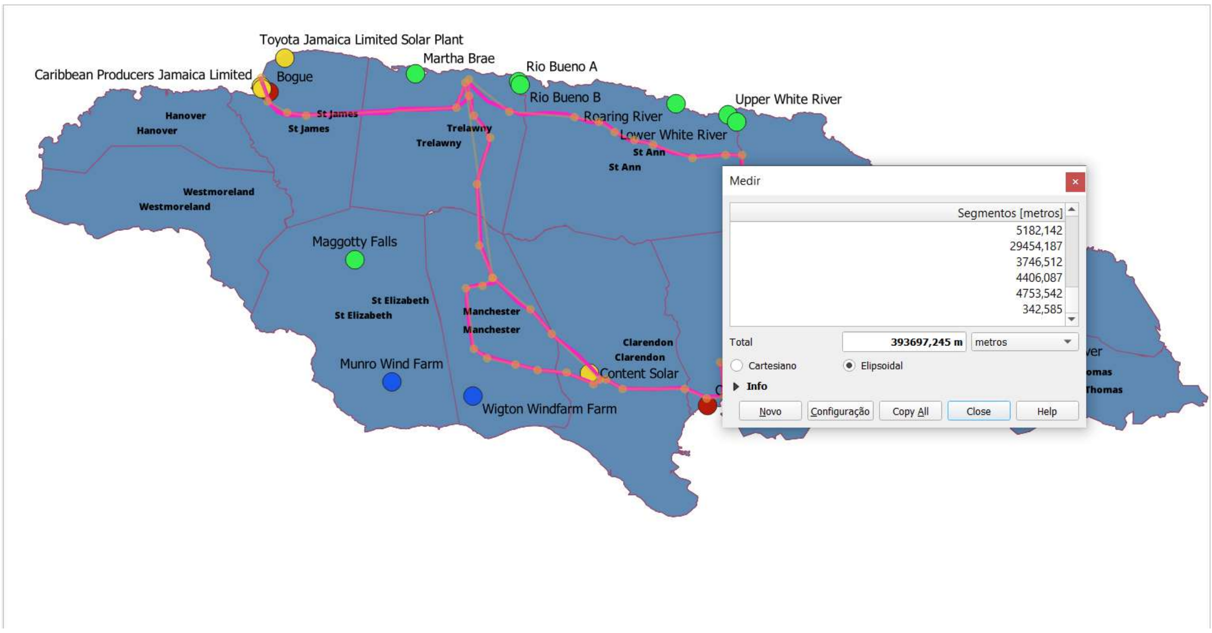

Figure 30 – Transmission Line- 138kV.

C.3 Transmission Line- 69kV

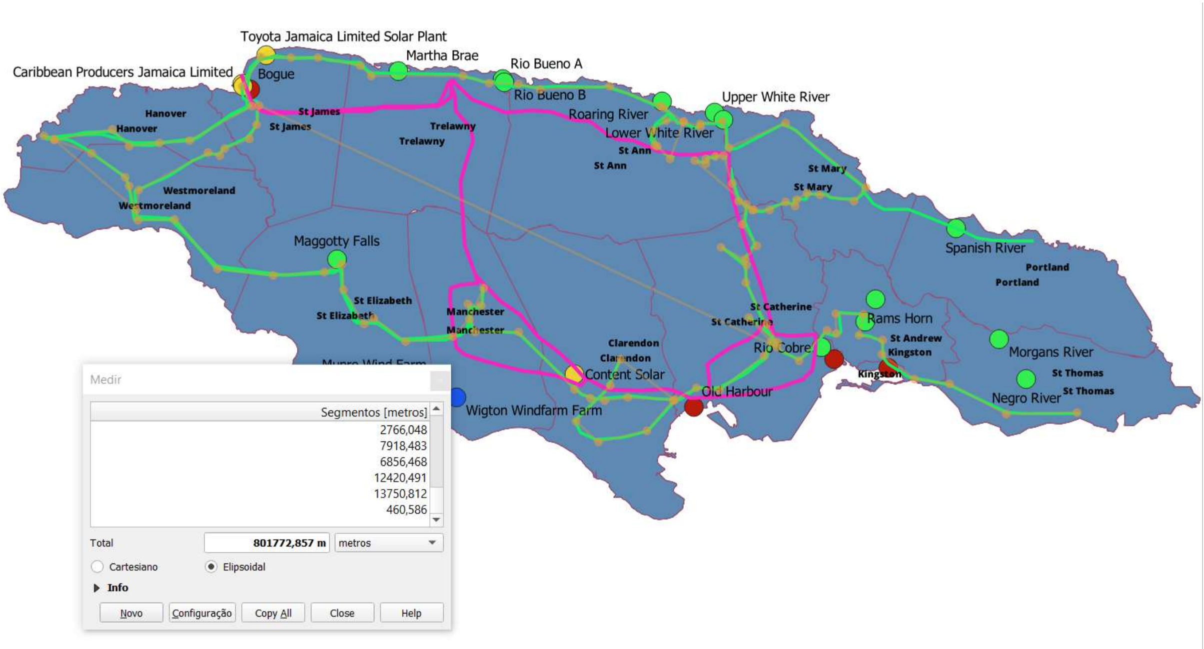

Figure 31 – Transmission Line- 69kV.

Appendix D – Maps Used in the Multicriteria Analysis

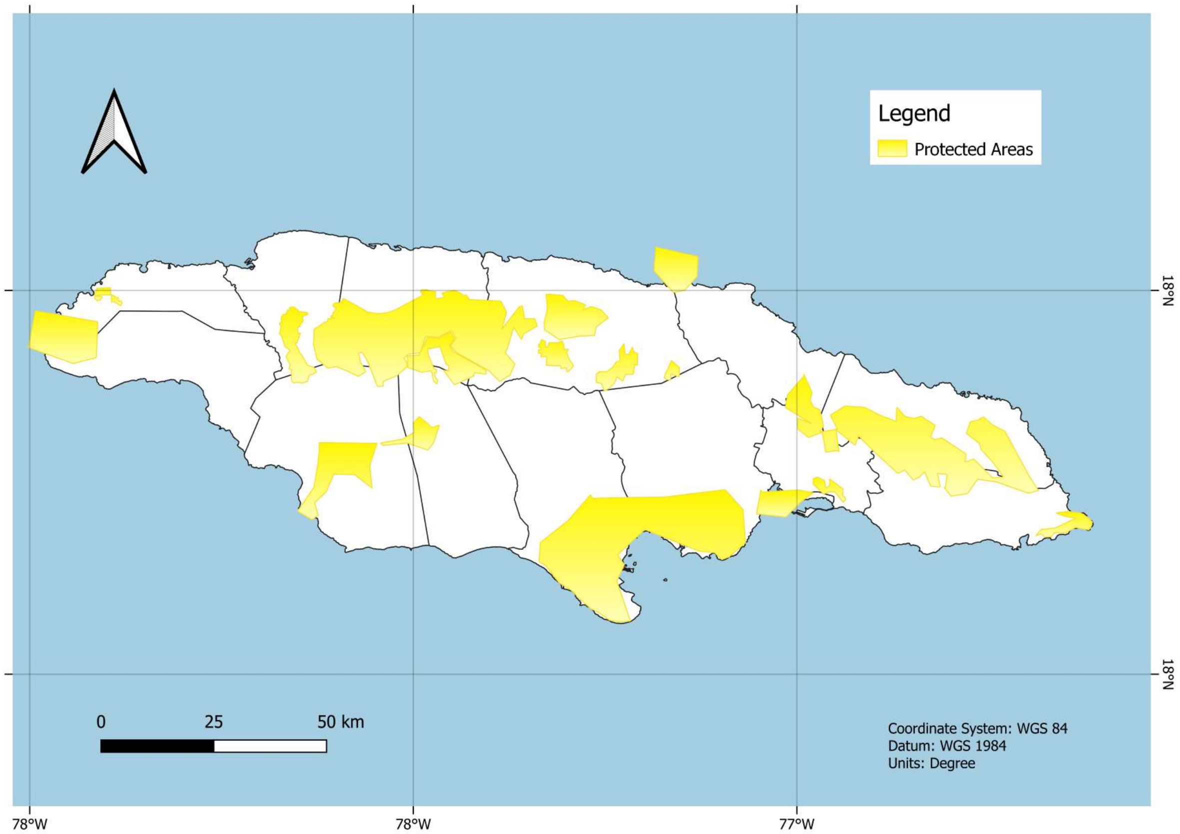

Figure 32 – Protected Areas in Jamaica.

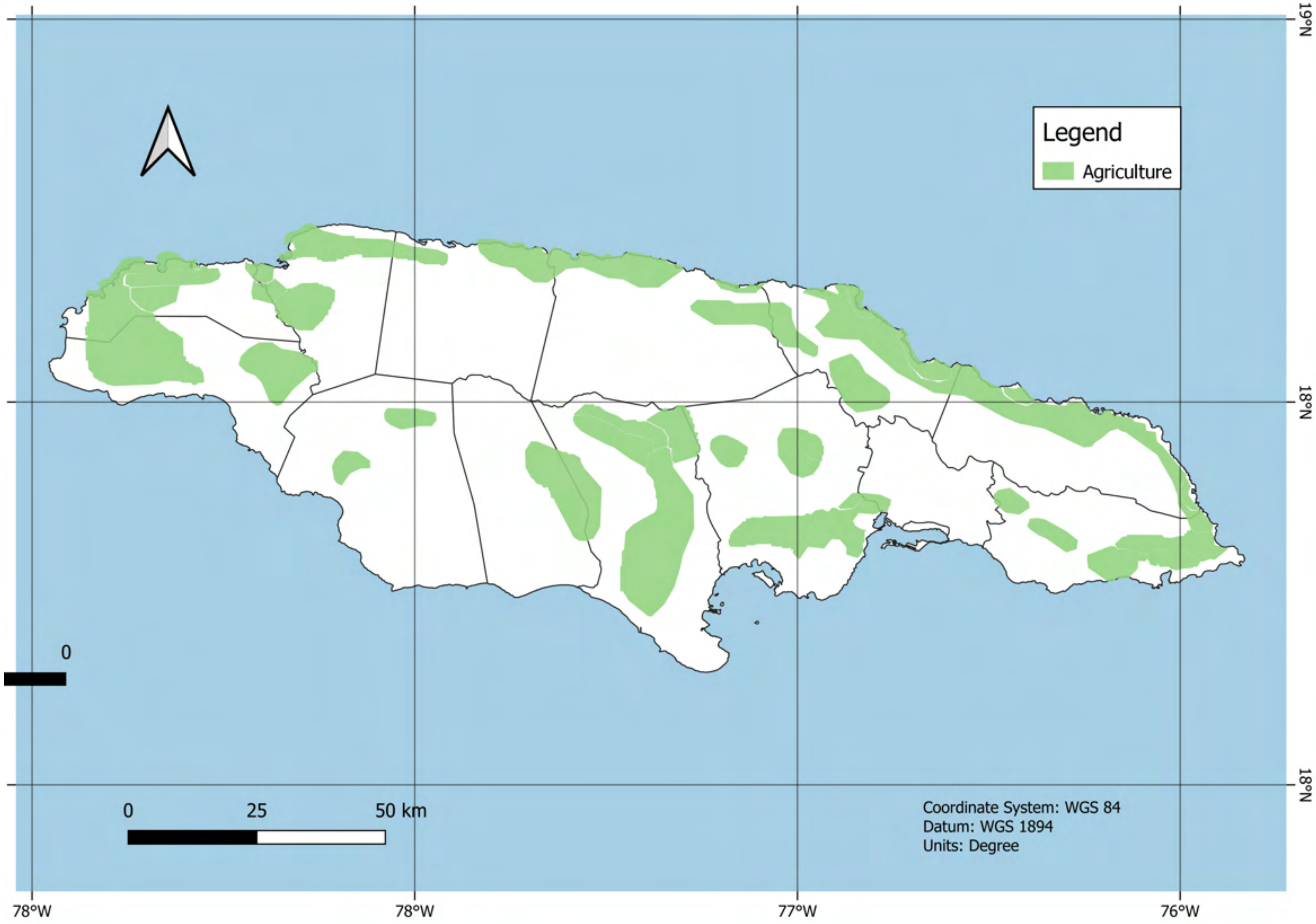

Figure 33 – Agricultural Areas in Jamaica.

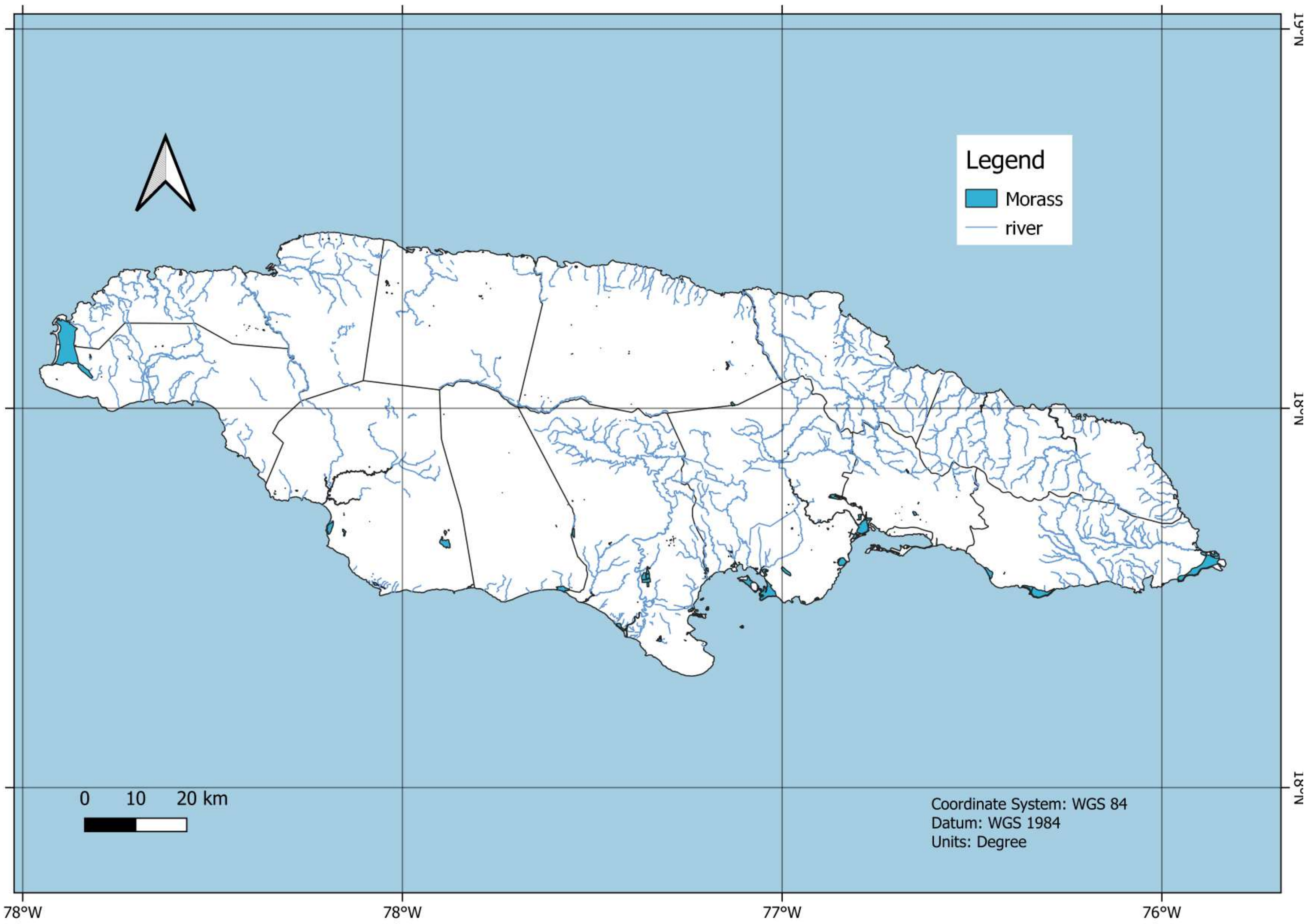

Figure 34 – Jamaican Wetland Areas.

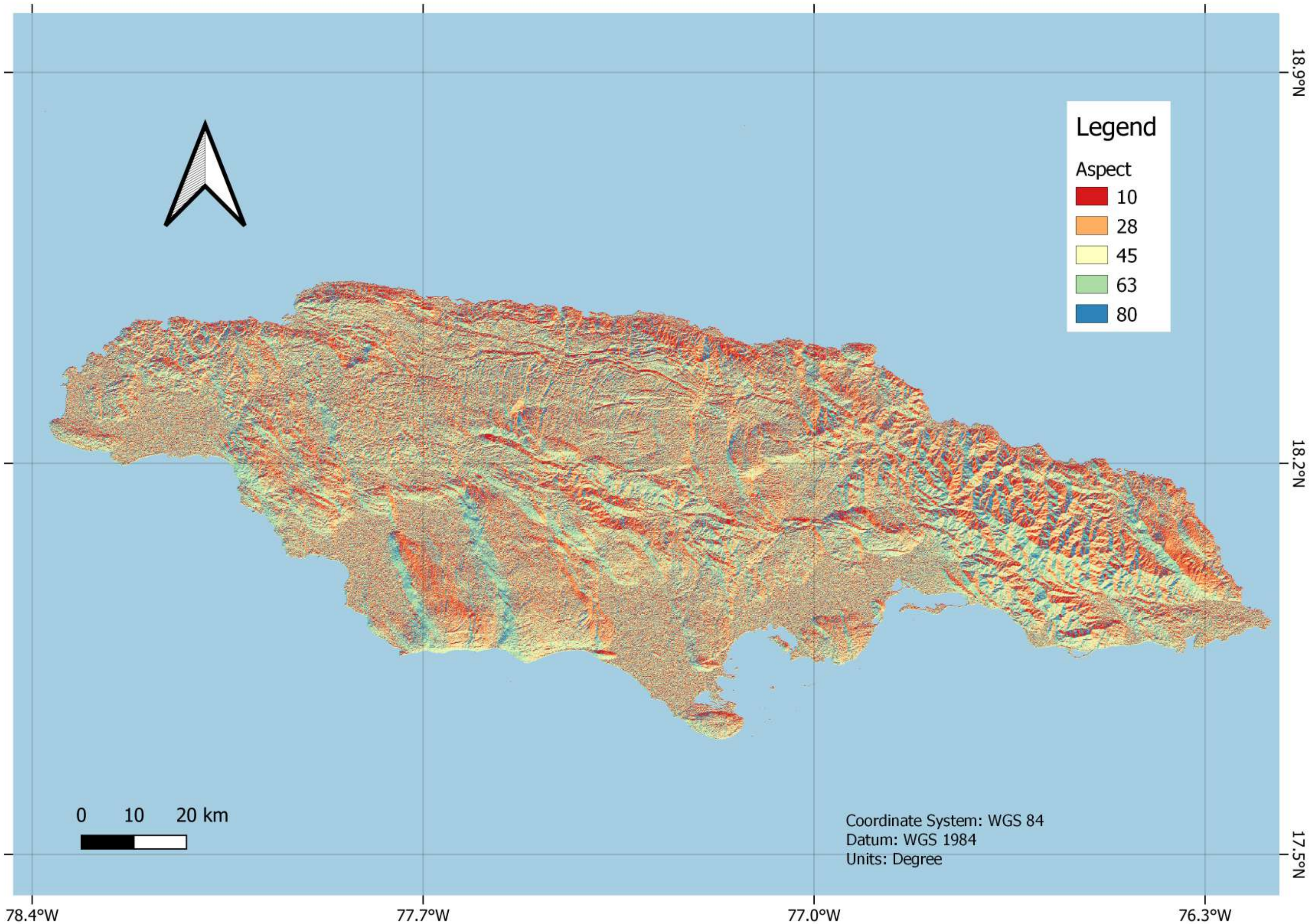

Figure 35 – Aspect Map of Jamaica.

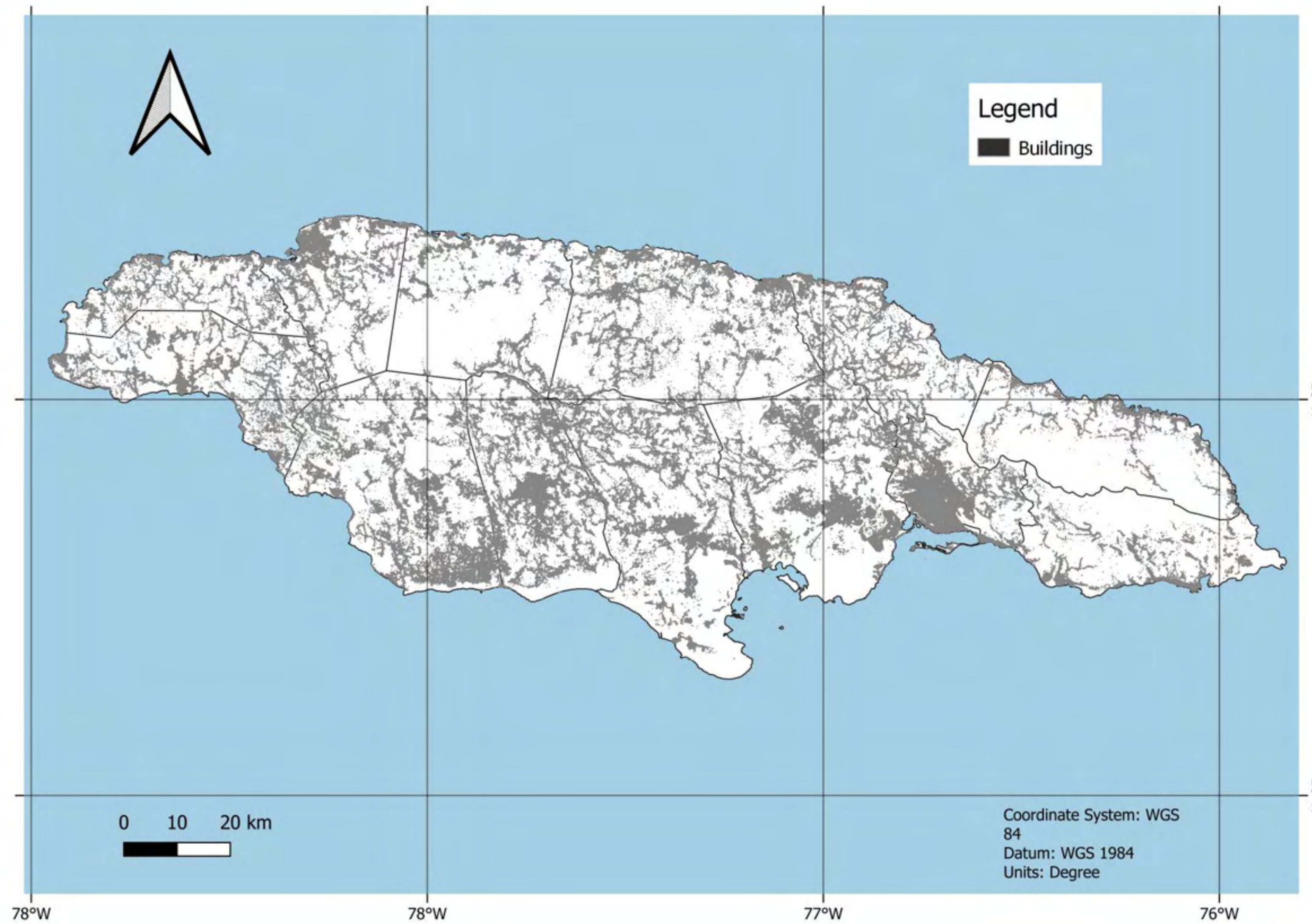

Figure 36 – Urban Areas.

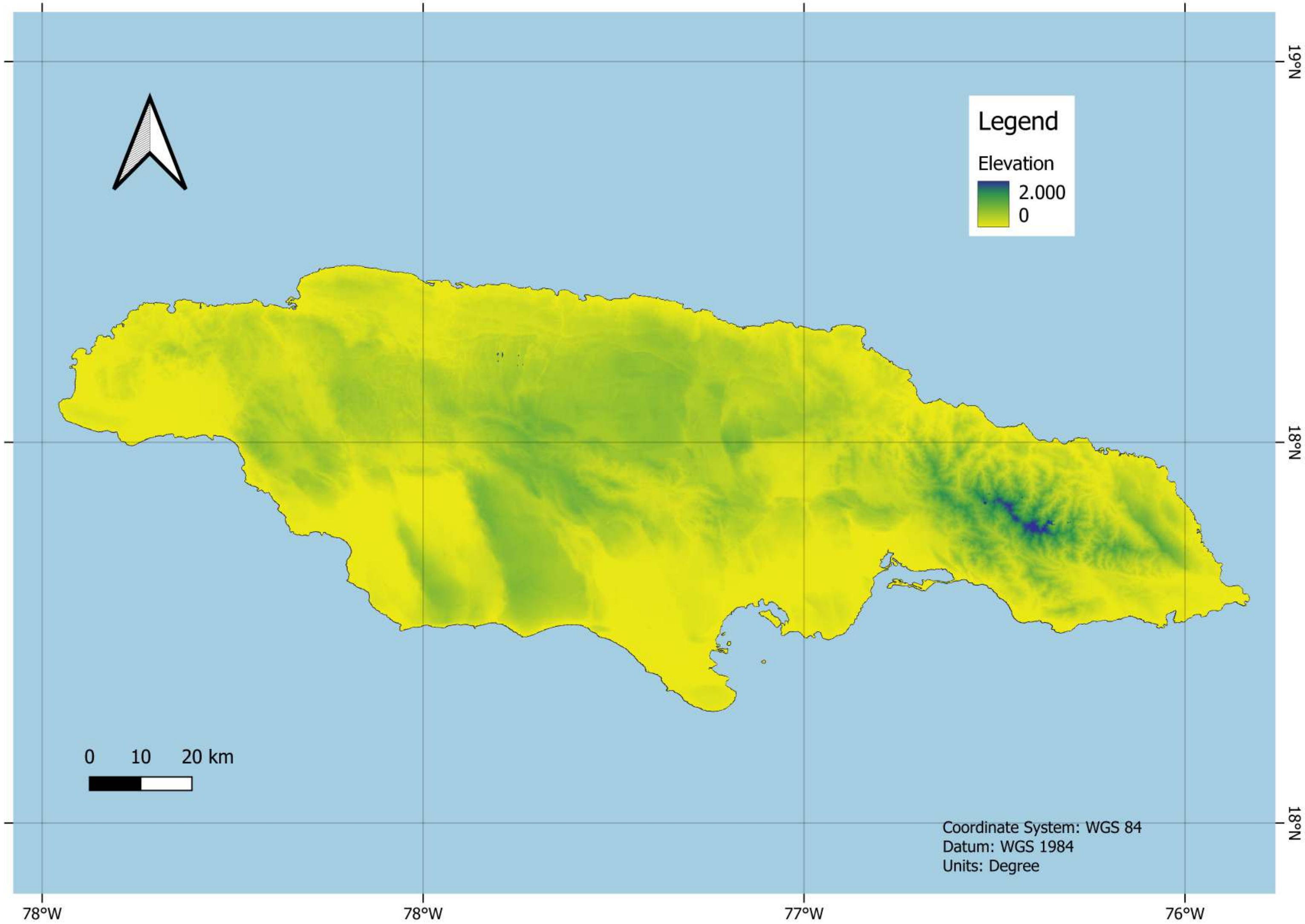

Figure 37 – Jamaican Elevation Map.

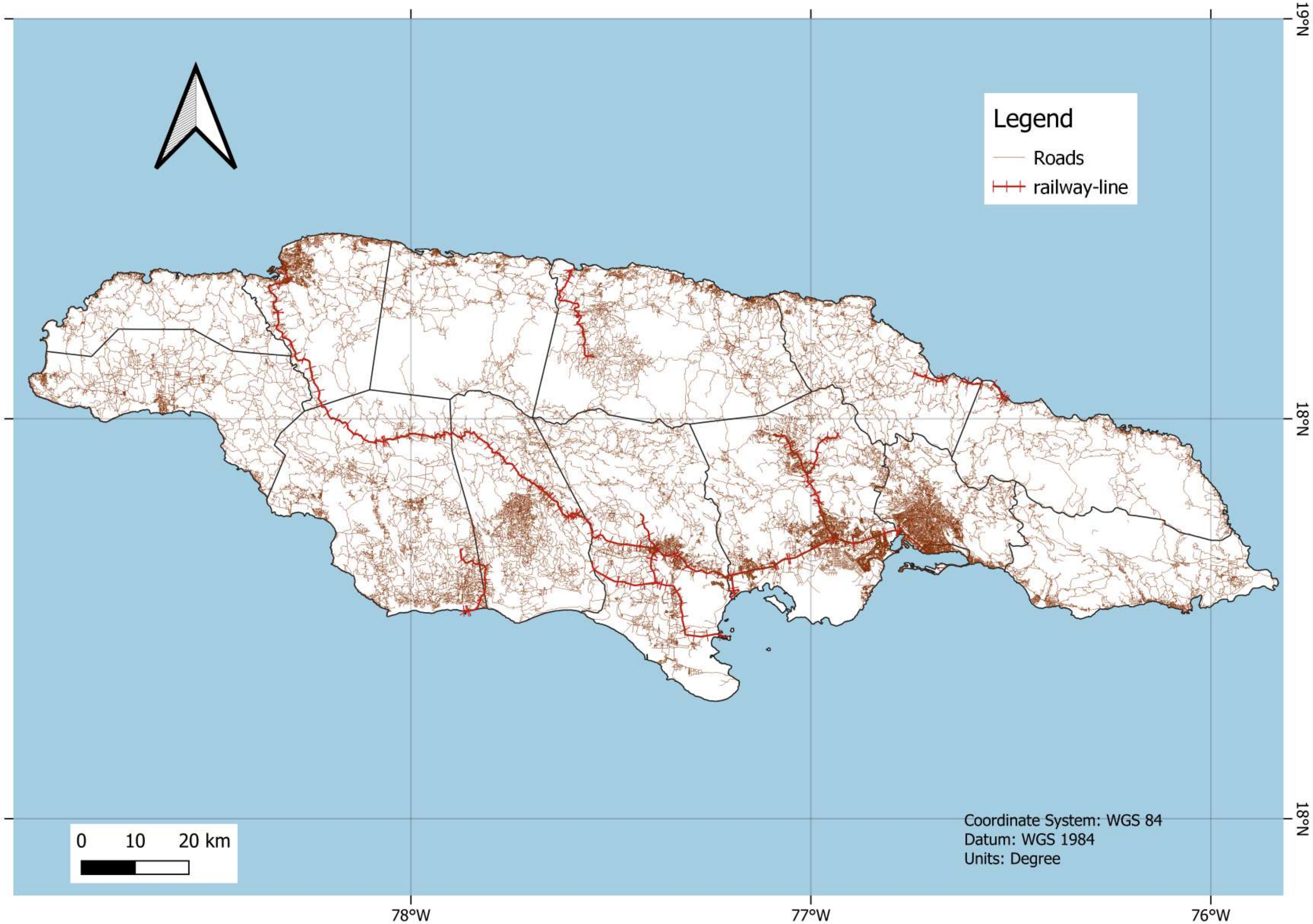

Figure 38 – Roads and Railways.

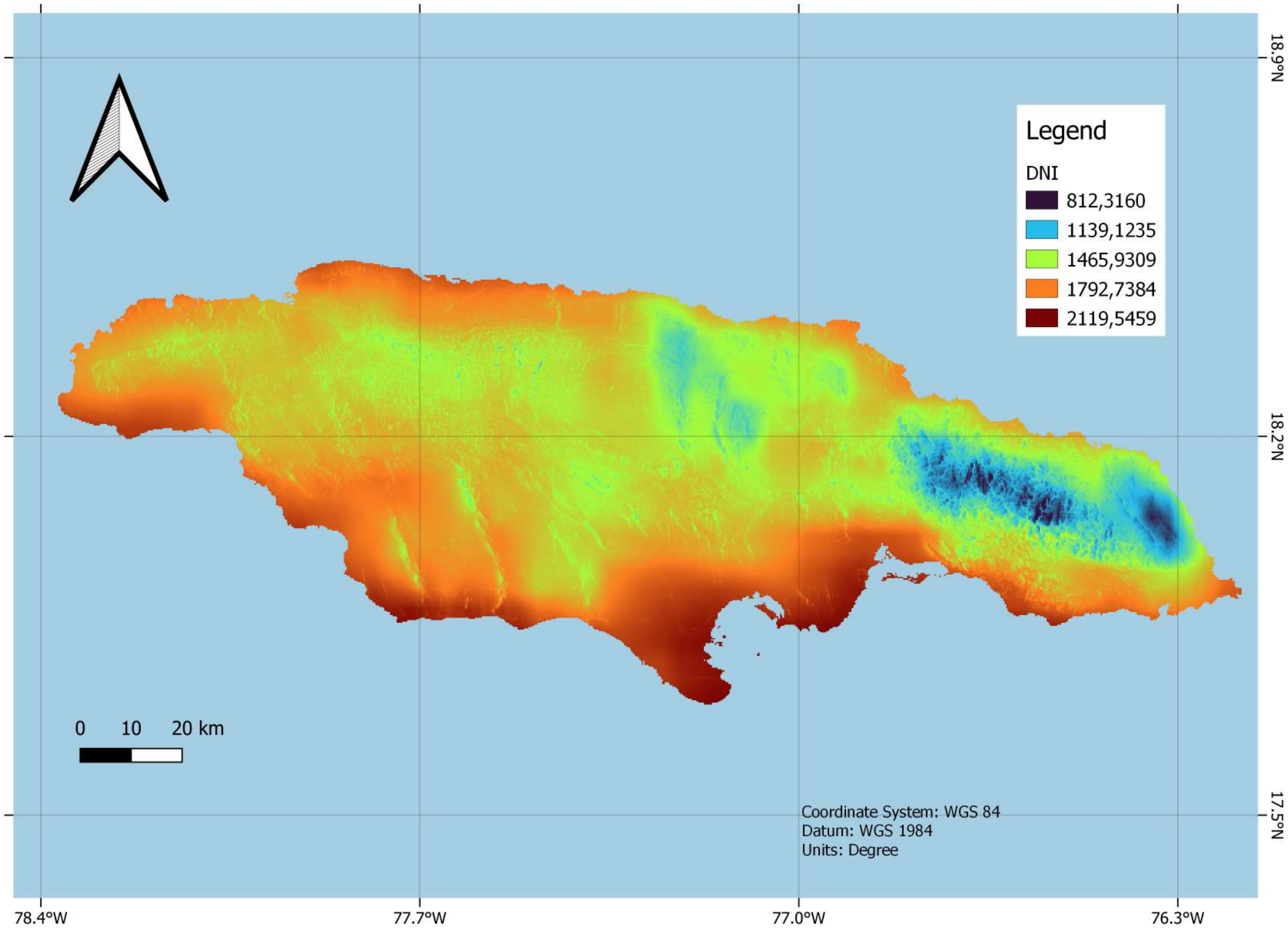

Figure 39 – Annual Direct Normal Irradiation of Jamaica.

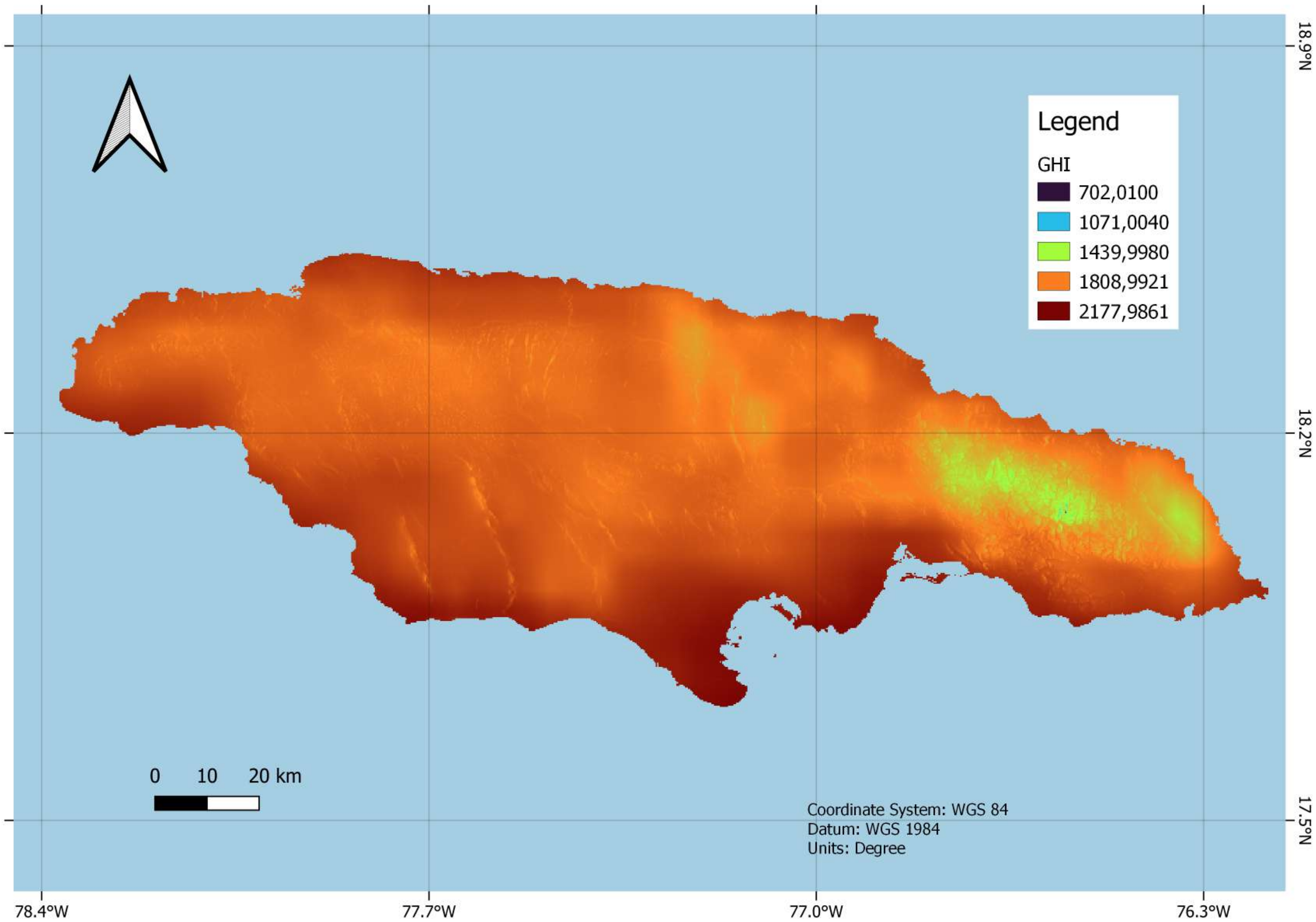

Figure 40 – Annual Global Horizontal Irradiation.

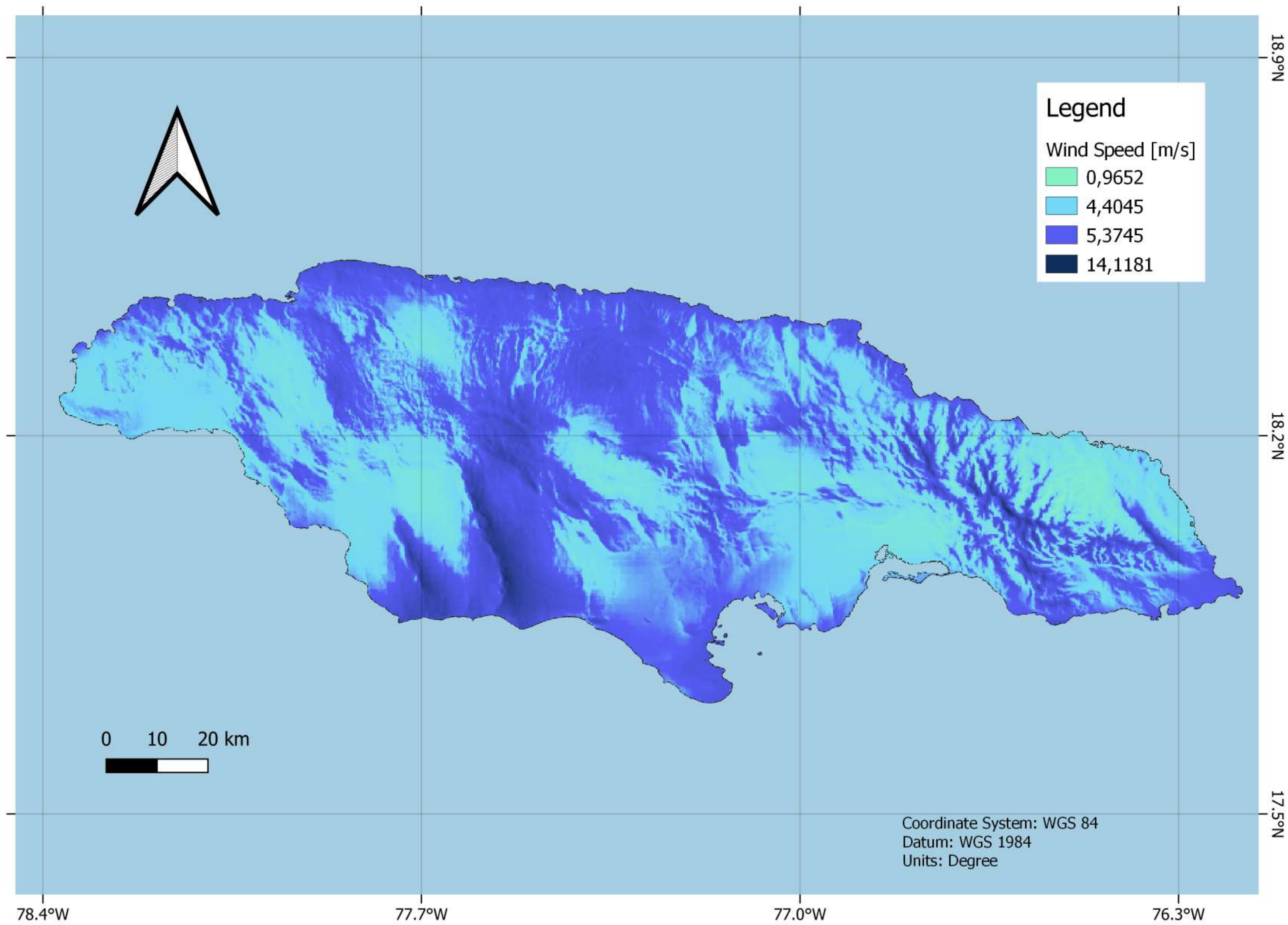

Figure 41 – Annual Wind Speed.

Appendix E – Areas of Classified Rasters

E.1 Area of Suitability Map Report

```
+-----------------------------------------------------------------------------+
|                         RASTER MAP CATEGORY REPORT                          |
|LOCATION: temp_location                              Wed Feb 01 09:51:58 2023|
|-----------------------------------------------------------------------------|
|          north: 18:31:30N    east: 75:58:12W                                |
|REGION     south: 17:01:21N    west: 78:22:03W                               |
|          res:      0:00:09    res:     0:00:09                              |
|-----------------------------------------------------------------------------|
|MASK: none                                                                   |
|-----------------------------------------------------------------------------|
|MAP: (untitled) (rast_63da606d24e017 in PERMANENT)                           |
|-----------------------------------------------------------------------------|
|                    Category Information                      |        square|
|#|description                                                 |        meters|
|-----------------------------------------------------------------------------|
|0| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .| 5,106,374,158|
|1| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .| 5,888,727,395|
|*|no data. . . . . . . . . . . . . . . . . . . . . . . . . . .|31,280,323,212|
|-----------------------------------------------------------------------------|
|TOTAL                                                         |42,275,424,765|
+-----------------------------------------------------------------------------+
```

Figure 42 – Area of Suitability Map Report.

E.2 Area of Solar Site Selection Report

```
+-----------------------------------------------------------------------------+
|                         RASTER MAP CATEGORY REPORT                          |
|LOCATION: temp_location                              Wed Feb 01 13:36:16 2023|
|-----------------------------------------------------------------------------|
|          north: 18:31:30.506743N    east: 75:58:08.494262W                 |
|REGION     south: 17:01:30.506743N    west: 78:22:08.494262W                 |
|          res:             0:00:36   res:             0:00:36               |
|-----------------------------------------------------------------------------|
|MASK: none                                                                   |
|-----------------------------------------------------------------------------|
|MAP: (untitled) (rast_63da94ff8946119 in PERMANENT)                          |
|-----------------------------------------------------------------------------|
|                   Category Information                       |        square|
|#|description                                                 |        meters|
|-----------------------------------------------------------------------------|
|2| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .|     1,170,658|
|3| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .|   170,989,818|
|5| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .| 2,241,971,650|
|4| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .| 3,454,634,126|
|1| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .| 5,134,091,861|
|*|no data. . . . . . . . . . . . . . . . . . . . . . . . . . . |31,245,917,507|
|-----------------------------------------------------------------------------|
|TOTAL                                                         |42,248,775,619|
+-----------------------------------------------------------------------------+
```

Figure 43 – Area of Solar Site Selection Report.

E.3 Area of Wind Site Selection Report

```
+-----------------------------------------------------------------------------+
|                         RASTER MAP CATEGORY REPORT                          |
|LOCATION: temp_location                              Fri Feb 03 02:12:42 2023|
|-----------------------------------------------------------------------------|
|          north: 18:31:23.767492N    east: 75:58:15.338344W                 |
|REGION    south: 17:01:14.767492N    west: 78:22:06.338344W                 |
|          res:             0:00:09   res:             0:00:09               |
|-----------------------------------------------------------------------------|
|MASK: none                                                                   |
|-----------------------------------------------------------------------------|
|MAP: (untitled) (rast_63dc97c9175019 in PERMANENT)                           |
|-----------------------------------------------------------------------------|
|                    Category Information                       |       square|
|#|description                                                  |       meters|
|-----------------------------------------------------------------------------|
|5| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |   44,323,532|
|4| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |  198,311,755|
|3| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |  247,556,237|
|2| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |2,763,983,848|
|1| . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . |7,746,565,555|
|-----------------------------------------------------------------------------|
|TOTAL                                                          |11,000,740,928|
+-----------------------------------------------------------------------------+
```

Figure 44 – Area of Wind Site Selection Report.

Appendix F – Sun Elevation Angle

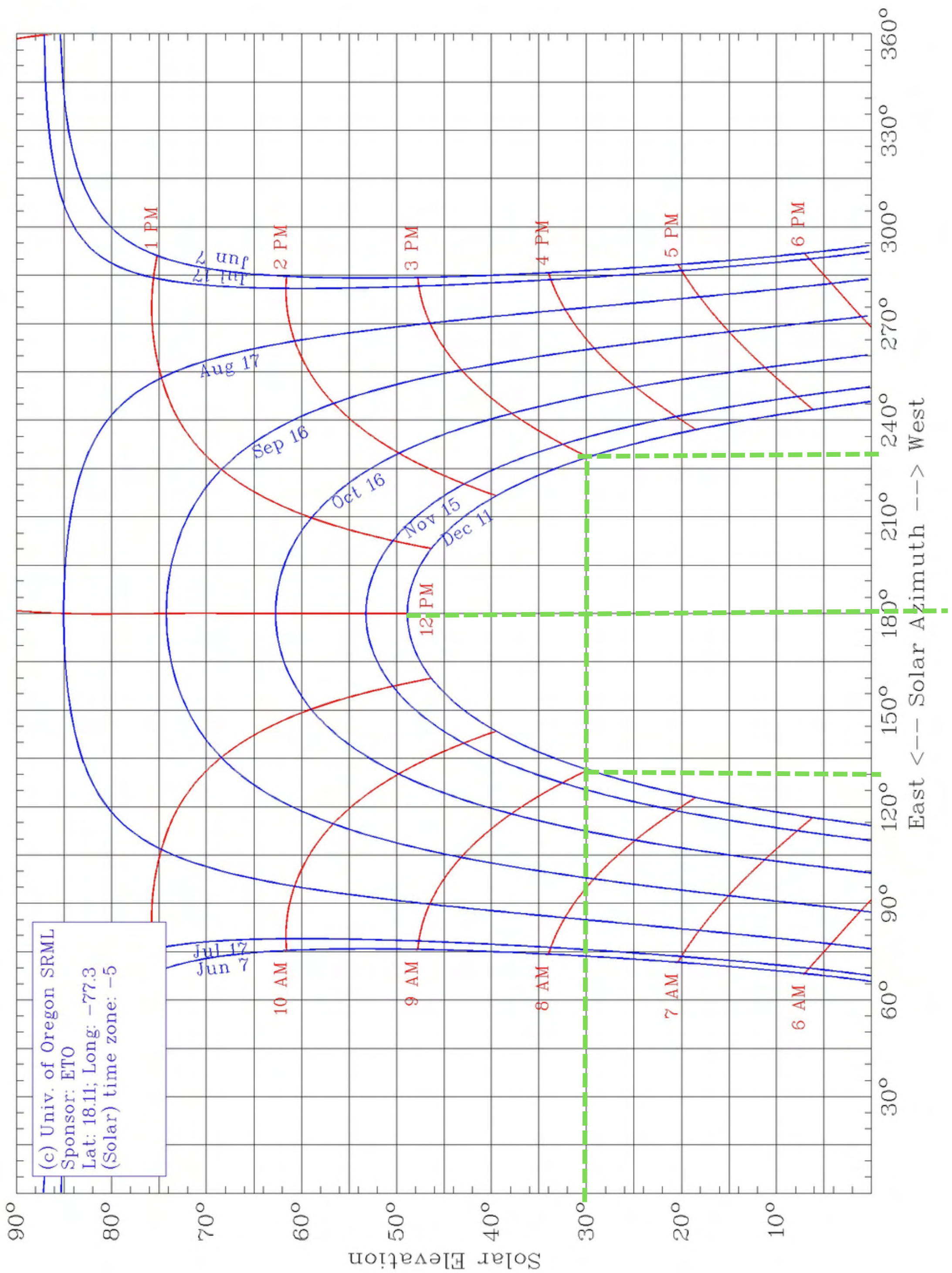

Figure 45 – Sun Elevation Angle.

Annex

Appendix A – Energy-related carbon dioxide emissions by source and sector for the United States, 2021 (million metric tons)

Total U.S. energy-related carbon dioxide (CO_2) emissions were about 4,872 million metric tons in 2021.

Energy-related carbon dioxide (CO_2) emissions by source and sector for the United States, 2021 (million metric tons)

	Residential	Commercial	Industrial	Transportation	Electric power	Source total
Coal	0	1	91	0	908	**1,001**
Natural gas	255	179	530	58	615	**1,637**
Petroleum	63	61	340	1,743	17	**2,224**
Other[1]					11	**11**
Electricity[2]	604	542	403	3		
Sector total	**922**	**783**	**1,364**	**1,803**	**1,551**	**4,872**

[1] Emissions from combustion of waste materials derived from petroleum and emissions from some types of geothermal power plants.
[2] Electricity-related CO_2 emissions are based on electric power sector electricity sales to the other sectors and the emissions associated with the generation of that electricity. The electric power total emissions of 1,551 million metric tons is not included in the source total emissions for all sectors (of 4,872 million metric tons) to avoid double counting.
Source: *Monthly Energy Review*, April 2022; preliminary data
Note: Sum of data in columns and rows may not equal the totals because of independent rounding.

Appendix B – JPS Annual Report 2020

05. JPS President & CEO, Michel Gantois; JPS Board Director, Mo Majeed; JPS Board Director, Emanuel DaRosa; and Former CEO of CB Group, Mark Haskins discuss the development of the 10 MW Combined Heat and Power plant at the CB Group's site at Hill Run in St. Catherine.

06. JPS linemen get busy carrying out important maintenance work.

26

OPERATIONAL STATISTICS

	Dec-31-20	Dec-31-19	Dec-31-18	Dec-31-17	Dec-31-16
OPERATING REVENUES ($000'S)					
Residential	358,467	319,451	338,772	317,205	283,459
Commercial & Industrial (Sml.)	367,183	393,331	393,306	363,187	304,727
Commercial & Industrial (Lge)	125,950	148,213	154,431	134,104	104,136
Other	37,106	20,158	21,745	22,373	20,212
TOTAL	**888,706**	**881,153**	**908,254**	**836,869**	**712,534**
AVERAGE NO. OF CUSTOMERS					
Residential	605,174	594,567	587,592	574,458	564,242
Commercial & Industrial (Sml.)	71,034	70,313	69,750	67,874	66,750
Commercial & Industrial (Lge.)	173	170	169	162	157
Other	498	482	486	450	419
TOTAL	**676,879**	**665,532**	**657,997**	**642,944**	**631,568**
NET GENERATION & PURCHASES (MWh)					
Steam & Slow Speed Diesel	459,696	1,229,418	1,354,599	1,466,690	1,668,268
Hydro	135,581	155,212	179,153	156,754	118,893
Gas Turbines	60,240	239,150	124,818	91,897	64,386
Combined Cycle Plant	740,009	815,713	901,834	820,466	705,634
Purchases	2,831,903	1,990,338	1,795,132	1,827,273	1,792,097
TOTAL	**4,227,429**	**4,429,831**	**4,355,536**	**4,363,079**	**4,349,278**
Losses & Unaccounted for (MWh)	1,135,883	1,156,503	1,153,885	1,155,940	1,169,970
Systems losses as a % of Net Generation	26.9%	26.1%	26.5%	26.5%	26.9%
Heat Rate JPS Thermal (Kj/kWh)	10,226	11,317	11,221	11,330	11,571
ENERGY SALES (MWh)					
Residential	1,157,455	1,099,666	1,062,732	1,068,594	1,077,148
Commercial & Industrial (Sml.)	1,315,407	1,426,194	1,394,572	1,381,376	1,380,791
Commercial & Industrial (Lge)	566,201	688,076	682,132	646,669	625,219
Other	52,483	59,392	62,214	110,500	96,150
TOTAL	**3,091,546**	**3,273,328**	**3,201,650**	**3,207,139**	**3,179,308**
AVERAGE USE & REVENUE per residential customer					
Annualized kWh Consumption/Customer	1,913	1,850	1,809	1,860	1,909
Annualized Revenues/Customer	592	537	577	552	502
US Dollars per kWh	0.31	0.29	0.32	0.30	0.26
Average billing exchange rate for period	142.00	134.02	129.30	128.57	125.10

27

Appendix C – Wind Turbine

C.1 Datasheet Vesta V112-3.3MW

Vestas V112-3.3

3,3 MW

✓ Power data
✓ 40 Pictures
✓ 1 Model

Pictures

Datasheet

Power

Rated power:	3,300.0 kW
Flexible power ratings:	-
Cut-in wind speed:	3.0 m/s
Rated wind speed:	13.0 m/s
Cut-out wind speed:	25.0 m/s
Survival wind speed:	-
Wind zone (DIBt):	-
Wind class (IEC):	Ib

Rotor

Diameter:	112.0 m
Swept area:	9,852.0 m²
Number of blades:	3
Rotor speed, max:	-
Tipspeed:	-
Type:	54.7
Material:	GFRP
Manufacturer:	-
Power density 1:	335.0 W/m²
Power density 2:	3.0 m²/kW

Figure 46 – Datasheet of the Vesta V112-3.3 Wind Turbines.

Appendix D – Solar Module

D.1 Datasheet Canadian Solar HiKu7 Mono PERC- 650W

NEW

CanadianSolar

HiKu7 Mono PERC

640 W ~ 665 W

CS7N-640|645|650|655|660|665MS

MORE POWER

665 W — Module power up to 665 W
Module efficiency up to 21.4 %

Up to 3.5 % lower LCOE
Up to 5.7 % lower system cost

Comprehensive LID / LeTID mitigation technology, up to 50% lower degradation

Compatible with mainstream trackers, cost effective product for utility power plant

Better shading tolerance

MORE RELIABLE

40 °C lower hot spot temperature, greatly reduce module failure rate

Minimizes micro-crack impacts

Heavy snow load up to 5400 Pa, wind load up to 2400 Pa*

12 Years — **Enhanced Product Warranty on Materials and Workmanship***

25 Years — **Linear Power Performance Warranty***

1st year power degradation no more than 2%
Subsequent annual power degradation no more than 0.55%

*According to the applicable Canadian Solar Limited Warranty Statement.

MANAGEMENT SYSTEM CERTIFICATES*

ISO 9001:2015 / Quality management system
ISO 14001:2015 / Standards for environmental management system
ISO 45001: 2018 / International standards for occupational health & safety

PRODUCT CERTIFICATES*

IEC 61215 / IEC 61730 / INMETRO
UL 61730 / IEC 61701 / IEC 62716
Take-e-way

* The specific certificates applicable to different module types and markets will vary, and therefore not all of the certifications listed herein will simultaneously apply to the products you order or use. Please contact your local Canadian Solar sales representative to confirm the specific certificates available for your Product and applicable in the regions in which the products will be used.

CSI Solar Co., Ltd. is committed to providing high quality solar products, solar system solutions and services to customers around the world. Canadian Solar was recognized as the No. 1 module supplier for quality and performance/price ratio in the IHS Module Customer Insight Survey, and is a leading PV project developer and manufacturer of solar modules, with over 52 GW deployed around the world since 2001.

* For detailed information, please refer to the Installation Manual.

CSI Solar Co., Ltd.
199 Lushan Road, SND, Suzhou, Jiangsu, China, 215129, www.csisolar.com, support@csisolar.com

Figure 47 – Datasheet Canadian Solar HiKu7 Mono PERC- 650W.