Python-Based Renewable Energy Resource Analyser (RERA): A Multi-Criteria Decision Support Tool for Renewable Energy Site Suitability in Namibia

Jeffrey N.S. SHIGWEDHA, Namibia, Ryan Theodore BENADE, Namibia and Oluibukun AJAYI, Namibia

Keywords: Renewable Energy, Site Suitability, Analytic Hierarchy Process, Spatial Decision Support, Namibia

Summary: Namibia faces a persistent energy deficit, with only about 56% of the population having access to electricity, and nearly 60% of the country's national demand is met through imports. To support evidence-based renewable energy planning, this study developed the Renewable Energy Resource Analyser (RERA), a Python-based, cross-platform GIS tool for analysing renewable energy site suitability. RERA integrates multiple spatial datasets and applies the Analytic Hierarchy Process (AHP) to evaluate and rank suitable locations for solar, wind, and green hydrogen developments.

The system was developed using Python 3.12 and key geospatial libraries, including Tkinter, Rasterio, GeoPandas, and NumPy, and incorporates geospatial datasets such as road networks, wind speeds, terrain, and existing electrical infrastructure datasets. RERA consists of two core modules: a Data Viewer for interactive visualisation of vector and raster data, and an AHP Suitability Module that enables pairwise comparison of spatial criteria, applies spatial decay to proximity-based datasets, and generates normalised suitability heatmaps.

The results demonstrate that combining AHP with spatial standardization techniques provides a transparent and reproducible framework for site selection. Operating fully offline, RERA is well suited to data-constrained environments and offers a scalable, open-source decision-support platform for renewable energy planning in Namibia and similar contexts.

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1. Introduction

Namibia faces a dual challenge of limited domestic electricity supply and persistent gaps in access for its population. The country's population is approximately three million, yet only 57 percent of residents have reliable access to electricity (Namibia Statistics Agency, 2024; Tracking SDG7, 2023). The current supply relies on a small set of large generation facilities and imports, a pattern that constrains long-term energy security and raises fiscal pressures on the national utility.

The national generation portfolio includes a 240 megawatt hydroelectric plant at Ruacana, a 120 megawatt coal-fired plant at van Eck, a 24 megawatt heavy fuel oil plant operated by Paratus at Walvis Bay with an additional unit anticipated in recent years, and a 5.78 megawatt solar installation at Trekkopje in the Erongo region (Energypedia, 2018). Namibia's annual consumption is roughly 3000 gigawatt hours, while domestic generation has historically ranged between about 1300 and 1700 gigawatt hours per year since 2000. The resulting shortfall has required substantial electricity imports, principally from neighbouring South Africa. These imports carry a high cost, for example, Nampower reportedly spent around N$3.4 billion on imports in 2021, covering roughly 60 per cent of the country's needs in that year (Heita, 2022).

These conditions create an imperative to expand local generation capacity and to direct investment where technical, environmental and socio-economic factors align. Renewable technologies present an avenue for increasing generation near demand centres and for extending electrification to underserved regions. National policy initiatives, such as the National Integrated Resource Plan and elements of the Harambee Prosperity Plan II, signal the government's intent to prioritise generation capacity expansion and encourage renewable energy development (Ministry of Industries, Mines and Energy, 2022; Republic of Namibia, 2023). Project proposals and discussions in regional fora further indicate growing interest in renewable projects at the time of this study (Lazarus, 2025).

Effective deployment of renewable generation requires decision-support tools that combine geospatial data, stakeholder preferences, technical constraints, and policy criteria into systematic site-selection workflows (Ramafikeng et al., 2025). Such tools help planners and investors evaluate trade-offs among land suitability, resource availability, environmental protection, grid proximity and socio-economic impacts. The Python-based Renewable Energy Resource Analyser (RERA), is developed as a multi-criteria decision support tool to address this need. RERA integrates spatial data visualization with a transparent weighting framework, enabling reproducible ranking of candidate sites for renewable energy projects in the Namibian context.

This paper describes the design, implementation, and evaluation of RERA. The tool is implemented in Python and couples geographic information system methods with the Analytic Hierarchy Process for weighting criteria and scoring sites. The contribution of this work is threefold. First, the tool provides an accessible platform for visualising national and regional energy-related datasets, allowing technical staff and non-specialists to better understand the distribution of resources and constraints. Second, the integration of a formal multi-criteria method produces repeatable site suitability outcomes that reflect user-defined priorities and expert judgement. Third, the study demonstrates the application of this combined approach in Namibia, including examples that illustrate how the choices of criteria and weights alter the final suitability rankings.

1.1 Objectives

The study was designed to produce a practical software prototype and to demonstrate its applicability to national energy planning. Specific objectives are as follows.

1. Develop a Python-based application that presents geospatial data on energy resources, infrastructure and constraints, and that supports interactive visual exploration of these datasets.
2. Implement a reproducible multi-criteria decision-making workflow that uses the Analytic Hierarchy Process to derive weights for site selection criteria, and that applies those weights to produce ranked suitability maps for renewable energy siting.
3. Evaluate the tool using case studies in Namibia, and assess how alternative weightings or data layers influence recommended sites and the implications for policy and investment decisions.

The Analytic Hierarchy Process provides a structured mechanism for eliciting relative importance across multiple criteria and for combining expert judgements with measured indicators (Saaty, 1980; Ajayi and Benade, 2025). In this study, the method is applied to reconcile conflicting objectives such as resource potential, environmental protection and proximity to transmission infrastructure, and to produce a transparent record of the assumptions that underlie suitability results. The subsequent sections present related work, describe the data and methods, detail the RERA implementation, and discuss results and implications for renewable energy planning in Namibia.

2. Materials and Methods

The development of the Renewable Energy Resource Analyser (RERA) utilizes a Geographic Information Systems Multi-Criteria Decision Analysis (GIS-MCDA) framework. This methodology is designed to transform heterogeneous spatial data into a unified decision-making index (Malczewski, 1999).

2.1 System Architecture

The development of RERA comprises several system components, including programming languages, software, and datasets as discussed below:

- **HTML (HyperText Markup Language):** A standard language used to create the structure of web pages. It defines elements like headings, paragraphs, links, images, and other content.

RERA was developed using Python 3.12. The application utilizes several specialized libraries for GIS and data processing:

- **Tkinter**: For the Graphical User Interface (GUI).
- **GeoPandas & Rasterio**: For handling vector and raster data.
- **Numpy & Scipy**: For mathematical calculations and matrix operations.
- **TkinterMapView**: For rendering OpenStreetMap base layers.
- **GeoServer**: An open-source server written in Java that allows users to share, process, and edit geospatial data, which supports various data formats and publishes data using open standards, making it highly interoperable (The Open Source Geospatial Foundation, n.d.).

The architecture is divided into three functional tiers: the Data Layer, the Logic Layer, and the Presentation Layer.

Data Layer/Backend: To manage heavy spatial computations, the system utilizes GeoPandas for vector processing and Rasterio for raster manipulation. A significant architectural hurdle was the high memory overhead of high-resolution GeoTIFF files. To solve this, GeoServer was implemented as an intermediary, serving data via Web Map Service (WMS) protocols to maintain application performance.

Logic Layer (Analytical Engine): The mathematical backbone uses NumPy for high-speed matrix operations required by the Analytic Hierarchy Process (AHP) and SciPy for calculating spatial decay constants.

Presentation Layer/Frontend: The interface was constructed using Tkinter, integrated with TkinterMapView. This allows for a dynamic, interactive environment where users can toggle layers, adjust opacity, and view metadata in real-time.

2.2 Data Acquisition

Ten datasets were strategically chosen to represent the multi-faceted nature of renewable energy siting in Namibia. Table 1 presents the datasets utilized in this study along with the primary justifications for the selection of each of these datasets

Dataset Name	Description/Attributes	Primary Justifications
NamRoads.geojson	Roads Found in Namibia Format: .geojson Source of Dataset: Digital Namibia (https://digitalnamibia.nsa.org.na/) CRS: EPSG:4326 - WGS 84	Included to account for logistical feasibility; heavy equipment for wind turbines and solar panels requires reliable road access for construction and long-term maintenance.
Powerlines.geojson	Power Lines in Namibia Format: .geojson Source of Dataset: Digital Namibia (https://digitalnamibia.nsa.org.na/) CRS: EPSG:4326 - WGS 84	These layers from Digital Namibia allow the model to prioritize sites near the existing national grid, reducing the "evacuation" cost of getting power from the plant to the consumer.
Substations.geojson	Existing Power Substations in Namibia Format: .geojson Source of Dataset: Digital Namibia (https://digitalnamibia.nsa.org.na/) CRS: EPSG:4326 - WGS 84	
R.E. Sources.geojson	Existing Renewable Energy Resources in Namibia Format: .geojson Source of Dataset: Digital Namibia (https://digitalnamibia.nsa.org.na/) CRS: EPSG:4326 - WGS 84	This dataset provides a "ground truth" for the model. By comparing existing solar or wind farms to the generated suitability heatmaps, you can validate that the RERA tool correctly identifies high-potential areas.

DNI.tif	Direct Normal Irradiation Levels in Namibia Format: .tif Source of Dataset: Global Solar Atlas (https://globalsolaratlas.info/map?c=-22.93816,17.072754,6) CRS: EPSG:4326 - WGS 84	Selected from the Global Solar Atlas because Namibia has some of the highest solar radiation levels globally; this layer identifies areas with the highest potential for solar thermal and PV power.
NamDEM.tif	A Digital Elevation Model depicting the terrain of Namibia Format: .tif Source of Dataset: Google Earth Engine CRS: EPSG:4326 - WGS 84	Sourced from Google Earth Engine to analyze terrain and slope. Steep slopes significantly increase construction costs and can cause shadowing for solar arrays.
NAM_wind-speed_100m.tif	Wind Speeds at 100 metres above Sea Level Format:.tif Source of Dataset: Global Wind Atlas (https://globalwindatlas.info/en/) CRS: EPSG:4326 - WGS 84	Sourced from the Global Wind Atlas to identify high-velocity wind corridors, particularly along the coast, which are essential for wind turbine efficiency.
Perennial Catchment Areas.geojson	Perennial Catchment Areas found in Namibia Format: .geojson Source of Dataset: Atlas of Namibia (https://www.uni-koeln.de/sfb389/e/e1/download/atlas_namibia/e1_download_physical_geography_e.htm#rivers1) CRS: EPSG:4326 - WGS 84	These layers serve a dual purpose: identifying water sources for Green Hydrogen production and acting as environmental "exclusion zones" where building might be restricted due to flood risks or ecological protection.
Major Rivers.geojson	Major Rivers found in Namibia Format: .geojson Source of Dataset: Atlas of Namibia (https://www.uni-koeln.de/sfb389/e/e1/download/atlas_namibia/e1_download_physical_geography_e.htm#rivers1) CRS: EPSG:4326 - WGS 84	

Land Tenure.geojson	The different types of land uses in Namibia Format: .geojson Source of Dataset: Digital Namibia (https://digitalnamibia.nsa.org.na/) CRS: EPSG:4326 - WGS 84	This dataset from Digital Namibia is critical for identifying land ownership types (e.g., communal, commercial, or protected areas). It helps planners avoid protected national parks or identify land where acquisition is more straightforward.

Table 1: Table of Datasets

2.3 Spatial Data Pre-processing and Standardization

Because the aforementioned datasets exist in disparate units (e.g., kWh/m^2 for solar potential versus meters for distance), Criterion Standardization was necessary to transform all values into a dimensionless scale from 0 (unsuitable) to 1 (highly suitable). For proximity-based data (such as distance to roads or power lines), the system uses Spatial Decay modelling (Hansen, 1959) to determine how suitability changes as one moves further away from a feature. The RERA tool offers three distinct logic models for this transformation:

1. **Linear Decay:** This model assumes suitability decreases at a constant rate and is used for features where influence is directly proportional to distance.

2. **Squared (Power) Decay:** This represents an aggressive drop-off, ideal for infrastructure (e.g., power lines) where immediate proximity is significantly more valuable than distal locations.

3. **Exponential Decay:** This models a rapid initial decay that tapers off, often used for environmental impacts or complex diminishing returns.

2.4 Analytic Hierarchy Process (AHP) Framework

The AHP framework reduces human bias by requiring users to perform Pairwise Comparisons (Adesina et al., 2024; Ajayi and Benade, 2025). Instead of weighing all factors at once, the user compares only two criteria at a time using a scale of 1 (equal importance) to 9 (extreme importance). The system processes these comparisons through a structured workflow:

1. **Comparison Synthesis:** The tool organizes every individual comparison into a reciprocal grid to determine the relative standing of each factor.

2. **Weight Derivation:** The system calculates a final "weight" or percentage of importance for each criterion, ensuring they all sum to 100%, by analyzing the relationships between all factors.

3. **Reliability Check:** To ensure the user's choices are logical and not contradictory (e.g., if A is better than B, and B is better than C, then C cannot be better than A), the system

calculates a Consistency Ratio (CR) (Ajayi and Benade, 2025; Adesina et al., 2026). A ratio below 0.1 confirms that the decision-making process is mathematically sound and reliable for the final analysis

2.5 Weighted Multi-Criteria Overlay

The final stage of the analysis is the Weighted Linear Combination (WLC), which synthesizes all the standardized data layers into a single result (Adesina et al., 2024). In this process, the system stacks every individual map layer, applying the specific weights calculated during the AHP phase to each pixel (Ajayi and Benade, 2025). The final output is a Suitability Heatmap, where values approaching 1.0 represent "Perfect Sites" that satisfy all technical, economic, and environmental requirements. This visual synthesis allows energy planners to instantly identify high-potential zones while seeing the direct trade-offs between natural resource availability and infrastructural constraints.

3. Results and Model Application

The model application has two distinct sections: the RERA Data Viewer and the AHP Suitability Module:

3.1 RERA Data Viewer

This is a module of the application that allows users to load, visualise and inspect various geospatial datasets and consists of the following parts:

- **Map Interface:** The map interface allows users to pan, zoom while raster data is displayed on a basemap loaded from OpenStreetMap.

- **Layer Controls and Sidebar:** A sidebar displays available data layers with checkboxes for users to toggle through each layer, while also allowing users to change the opacity of a layer. The application loads all datasets found in the /data folder and displays them in an interactive GUI.

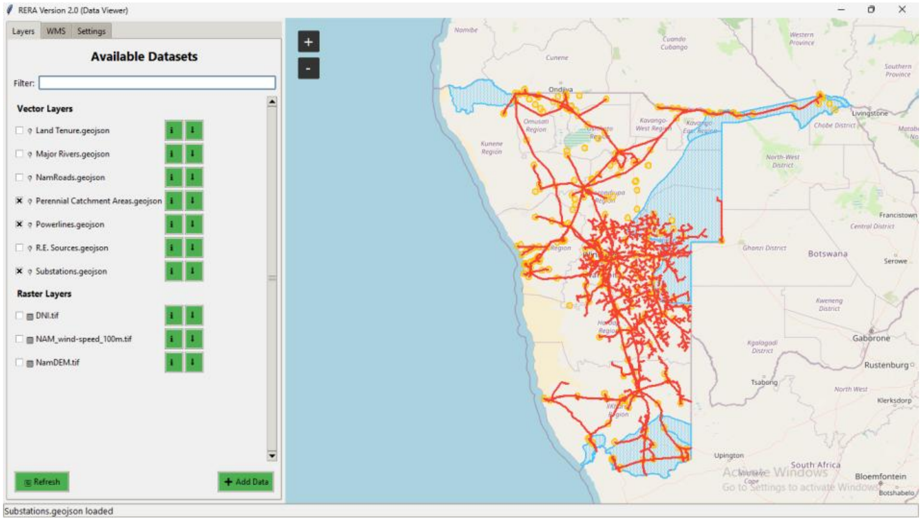

Figure 1: Vector dataset viewing section in the RERA app.

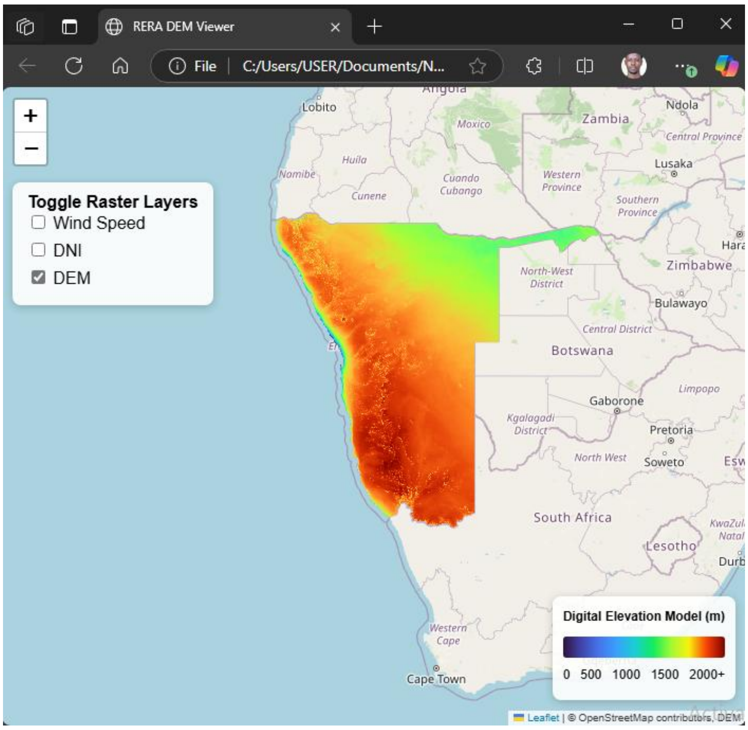

Figure 2: Raster dataset viewing section on webpage.

- **Spatial Data Clearinghouse:** Users can preview their desired layers and have an option to view each dataset's metadata. Users can then download individual datasets from the sidebar.

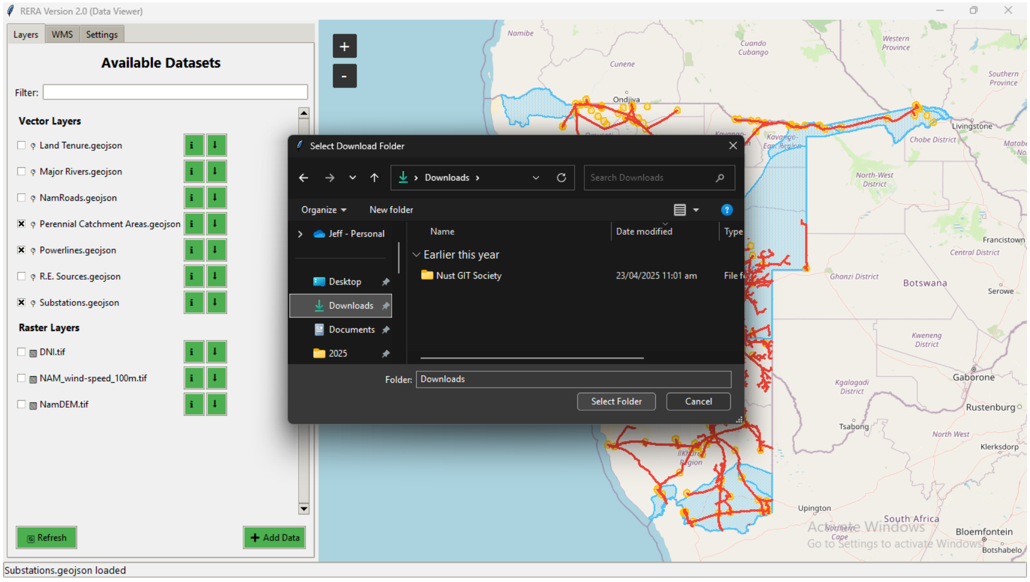

Figure 3: Popup window where end users select where the downloaded dataset should be stored.

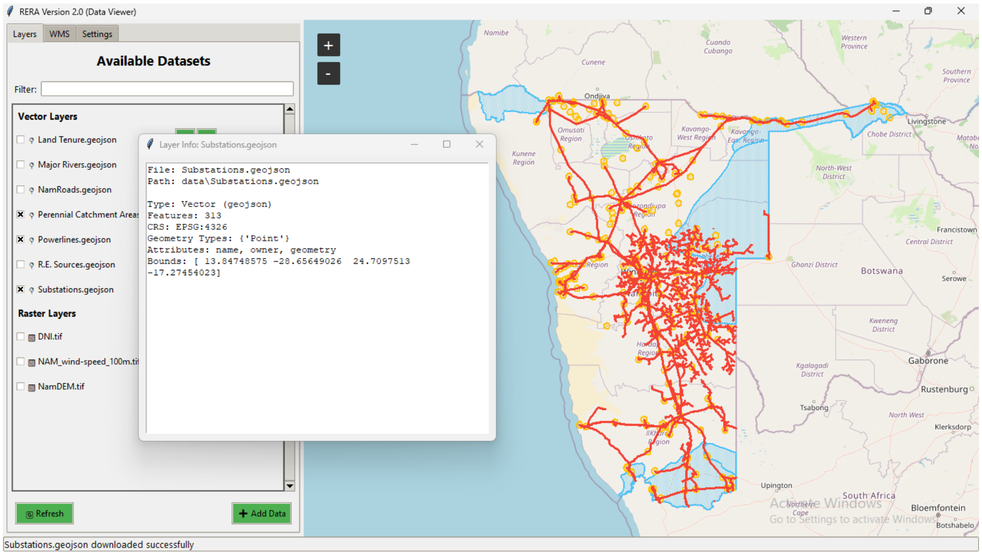

Figure 4: Metadata about Renewable Energy Resource Datasets.

3.2 AHP Suitability Module

The Suitability Module is the session of RERA that allows users to implement the AHP to support weighted decision-making across multiple datasets that generate normalized raster outputs (heatmaps) that highlight the most suitable areas for renewable energy projects. It consists of the following sections.

- **Dataset Loader:** Allows users to upload desired datasets for spatial analysis. In the dataset loader: Vector datasets like roads, rivers, and powerlines are turned into raster layers using a method called spatial decay. This helps show how important it is to be close to those features.

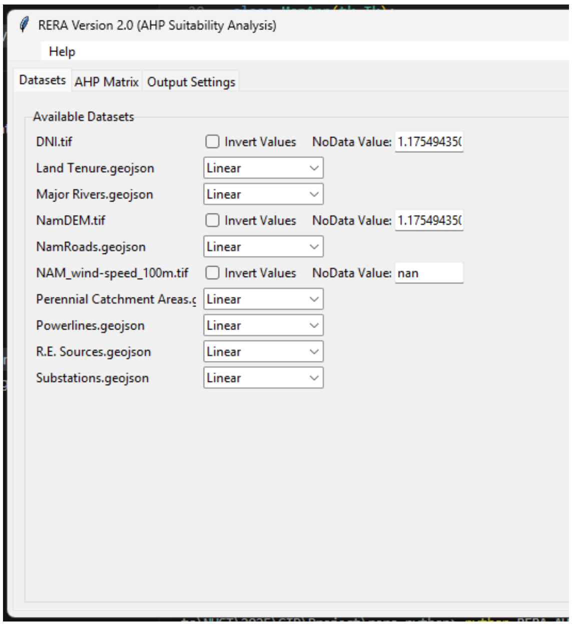

Figure 5: Dataset Loader for AHP section of RERA.

- **AHP Matrix:** Allows users to allocate important values within a pairwise matrix. Outlined in red are the functionalities that allow users to load or clear importance value presets (whether solar, wind or green hydrogen farms) within the pairwise matrix.

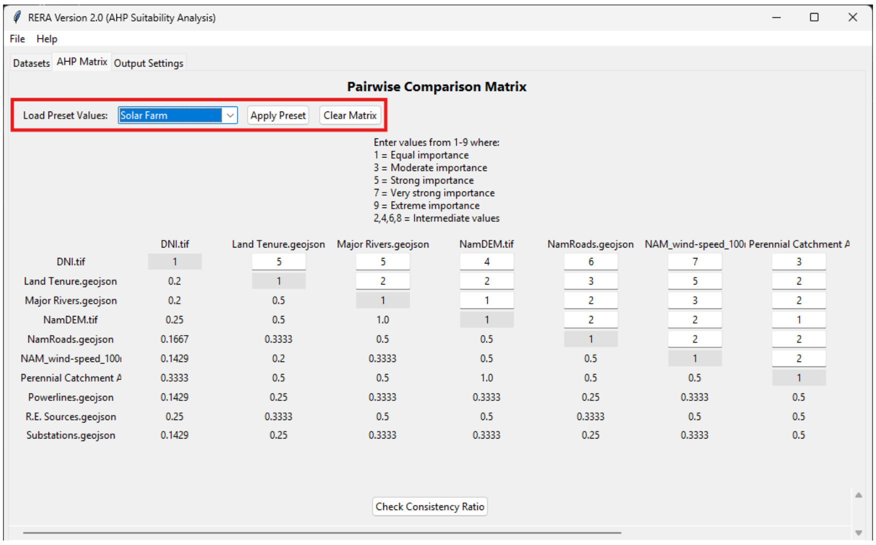

Figure 6: RERA AHP Pairwise Matrix.

	DNI	LAND TENURE	MAJOR RIVERS	DEM	ROADS	WIND SPEED	CATCHMENT AREA	POWERLINES	R.E. SOURCES	SUBSTATIONS
DNI	1	5	5	4	6	7	3	7	4	7
LAND TENURE	0.2	1	2	2	3	5	2	4	3	4
MAJOR RIVERS	0.2	0.5	1	1	2	3	2	3	2	3
DEM	0.25	0.5	1	1	2	2	1	3	2	3
ROADS	0.166667	0.333333	0.5	0.5	1	2	2	4	3	4
WIND SPEED	0.142857	0.2	0.333333	0.5	0.5	1	2	3	2	3
CATCHMENT AREAS	0.333333	0.5	0.5	1	0.5	0.5	1	2	2	2
POWERLINES	0.142857	0.25	0.333333	0.333333	0.25	0.333333	0.5	1	2	3
R.E. SOURCES	0.25	0.333333	0.5	0.5	0.333333	0.5	0.5	0.5	1	2
SUBSTATIONS	0.142857	0.25	0.333333	0.333333	0.25	0.333333	0.5	0.333333	0.5	1

Table 2: Table of Pairwise Values for Determining Solar Farms

- **Output Hub**: Allows users to determine where their suitability output will be stored. Outlined in red are the functionalities that allow users to export the importance values, weights and dataset settings into a CSV file and Outlined in green are the functionalities that allow users to select a GeoJSON file that clips the output to a desired shape.

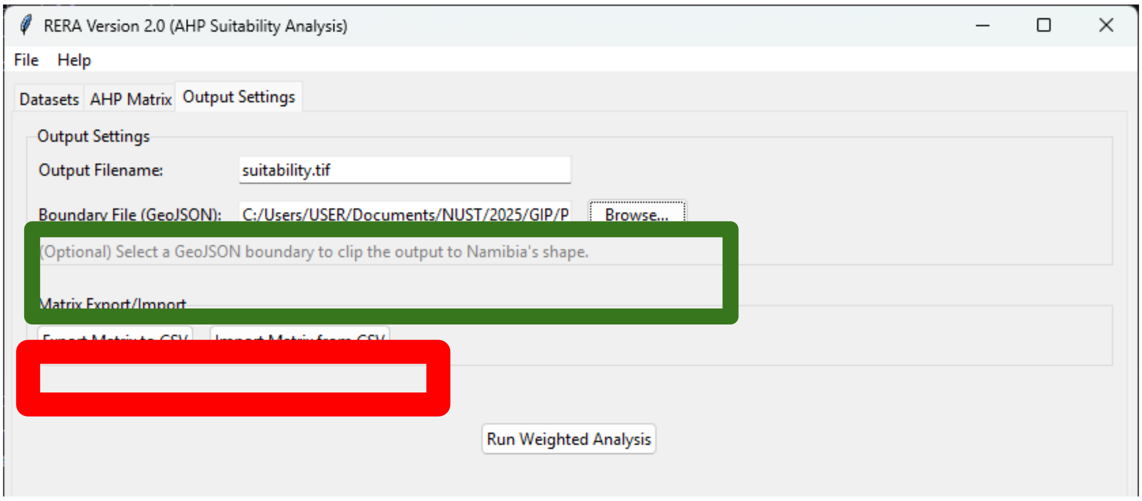

Figure 7: Output Hub for Exporting Dataset

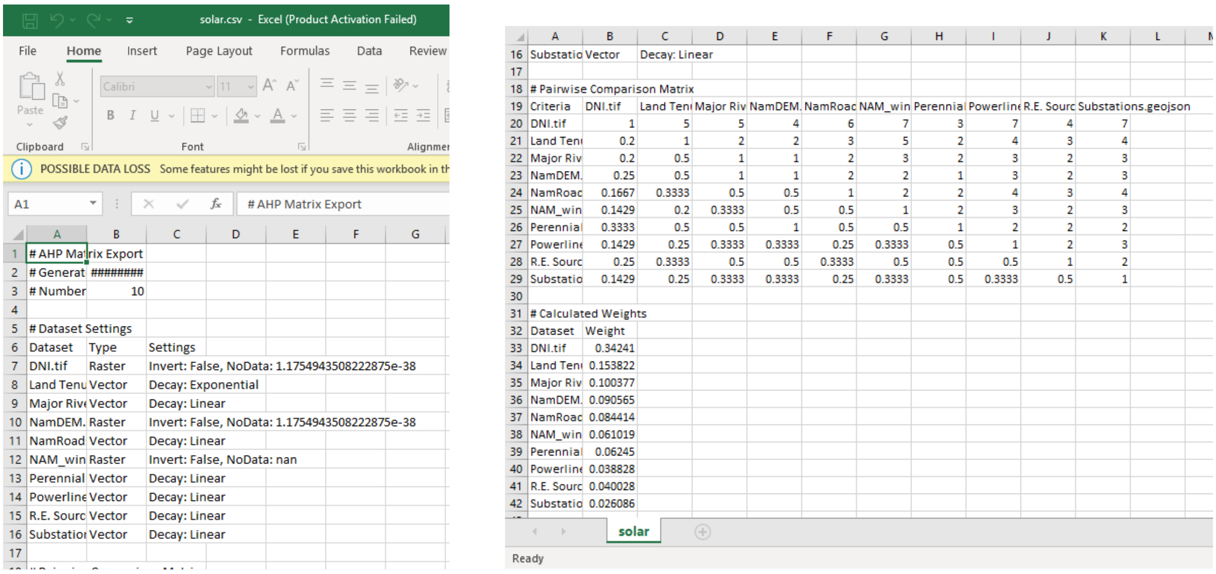

Figure 8: Exported CSV file containing Solar Farm AHP Information

It should be noted that the pairwise comparison values used in the AHP matrix in Figure 6 & Table 2 above for implementing solar farms (as well as the other two presets for wind & green hydrogen farms) were assigned arbitrarily for the purpose of developing and testing the prototype application's functionality.
These values were not derived from expert consultation but were instead selected to simulate realistic relative importance relationships between criteria and to validate the end-to-end implementation of the AHP workflow. As such, the resulting weights and suitability outputs should be interpreted strictly as demonstrative rather than prescriptive. In a production or decision-support context, these values would need to be refined through structured expert judgment, policy guidelines, or sensitivity analysis to ensure decision validity and reliability.
To transform the raw computational output of the RERA model into a decision-support tool, the abstract floating-point values (ranging from 0.0 to 1.0) must be classified into distinct

categories. In this study, the continuous raster data is reclassified using a graduated scale to represent varying degrees of suitability.
For cartographic representation, the following color ramp in Table 3 below is utilized. This ramp provides a high-contrast, perceptually linear sequence that effectively differentiates subtle variations in the dataset.

Floating-point Values	Colour Utilised	Level of Suitability
0.00 – 0.20	Dark Red	Least Suitable
0.21 – 0.40	Orange	Low Suitability
0.41 – 0.60	Yellow	Moderate Suitability
0.61 – 0.80	Light Green	High Suitability
0.81 – 1.00	Dark Green	Highly Suitable

Table 3: Colour Ramp Categories

With the solar farm preset achieving a consistency ratio (CR < 0.1) within the AHP framework of about 6.3% (or 0.063, with the Direct Normal Irradiation taking the highest priority of the datasets with a percentage of 34.2 %, while existing substations/infrastructure taking the lowest priority of the datasets with a percentage of 2.6 %), resulting in the creation of the suitability map presented in Figure 9 with clear distinctions of suitable areas in Namibia, with the percentage coverage of each of the suitability classes presented in Table 4.

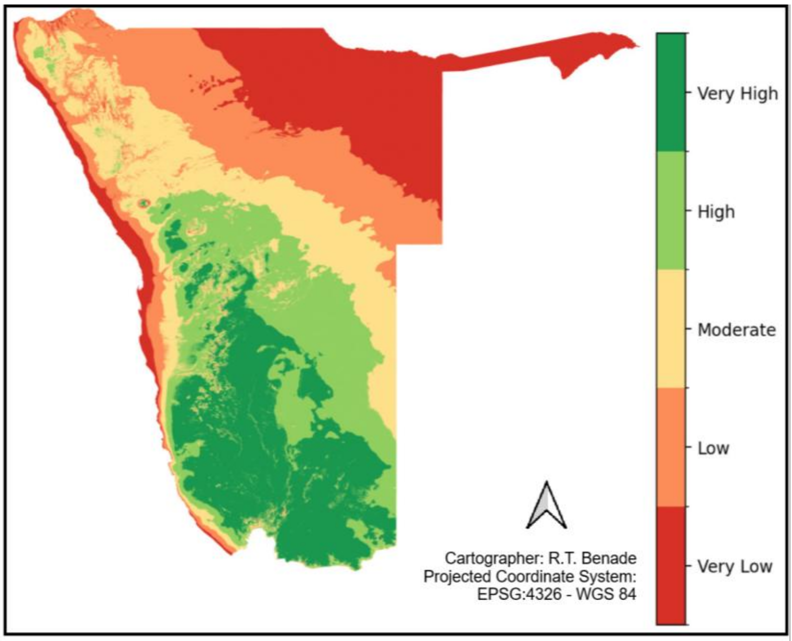

Figure 9: Final Solar Farm Suitability Map

Suitability Level	Area (km2)	Area Coverage % of Namibia
Very High	159915.066	19.37 %

High	162726.787	19.71 %
Moderate	165623.806	20.06 %
Low	167353.797	20.27 %
Very Low	168211.705	20.37 %

Table 4: Suitability Level Area Percentage in Namibia

The resulting spatial distribution reveals a remarkably balanced landscape, with each suitability category occupying approximately 20% of Namibia's total land area. This near-even split provides a clear, actionable hierarchy for land-use planning; it effectively isolates the most productive or suitable areas, which span about 322,641 km^2 (the "High" and "Very High" zones) for immediate investment. The "Very High" green zones, predominantly concentrated in the southern and central-western regions, represent the intersection of optimal solar resource availability and favourable terrain, providing a robust justification for regional development focus.

From a strategic perspective, this map serves as a high-fidelity blueprint for Namibia's renewable energy transition. The sharp distinctions between the northern "Very Low" zones and the southern "Very High" zones likely reflect a combination of higher cloud cover or environmental constraints in the north versus the arid, clear-sky conditions of the south. Because the model is resource-led rather than infrastructure-constrained, it justifies a "build-to-resource" approach, suggesting that the expansion of the national power grid should be directed toward these dark green zones to maximize the country's sovereign energy security and export potential.

Conclusion

This study presents the design and implementation of the Renewable Energy Resource Analyser (RERA), a Python-based spatial decision-support system developed to address Namibia's growing need for evidence-based renewable energy planning. The application successfully demonstrates how heterogeneous spatial datasets can be transformed into a unified, transparent, and reproducible framework for site suitability assessments of solar, wind, and green hydrogen energy developments.

The results confirm that multi-criteria decision analysis, when combined with spatial normalization and decay-based proximity modelling, provides a powerful mechanism for balancing technical, environmental, and infrastructural constraints. The generated suitability heatmap is meant to illustrate how priority regions emerge through the weighted interaction of key criteria such as resource availability, land tenure, terrain, infrastructure proximity, and environmental considerations. Importantly, the modular design of RERA allows users to interrogate each stage of the analytical workflow, thereby enhancing transparency and interpretability critical requirements for planning and policy-oriented applications.

While the AHP pairwise comparison values used in this prototype were intentionally arbitrary and designed solely for functional validation, the system architecture is robust enough to support expert-driven weighting, sensitivity analysis, and policy-aligned decision frameworks in future deployments. As such, RERA should be viewed not as a prescriptive planning solution, but as a flexible analytical platform capable of supporting informed decision-making when coupled with domain expertise and stakeholder input.

In conclusion, RERA demonstrates the practical feasibility of deploying open-source geospatial technologies and multi-criteria decision methodologies to support renewable energy planning in data-constrained environments. The tool provides a solid foundation for further enhancement, including expert calibration, large-scale deployment, and integration with national energy planning systems. Beyond Namibia, the framework offers a transferable blueprint for other regions seeking transparent, adaptable, and locally relevant renewable energy site selection tools.

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Biographical Notes

Jeffrey Shigwedha is a Geographic Information Technology Honors student at the Namibia University of Science and Technology (NUST).

His practical experience includes a GIS internship at the Ministry of Industry, Mines and Energy in Namibia, where he worked as a web-map application developer and data assistant. A role that provided him with end-to-end exposure to geospatial database management, cartographic styling and web service publication. He has further strengthened his data management skills through his current internship at the Namibia Statistics Agency, contributing to the National Housing Information System by supporting large-scale data digitisation, quality control, and GIS-supported information management.

Alongside his technical work, Jeffrey has demonstrated leadership and professional engagement. He serves as Project Coordinator for the NUST Geoinformation Technology Society, where he is responsible for project planning, logistics coordination, and liaison with external partners.

In terms of scholarly activity, Jeffrey has submitted an abstract to the FIG Working Week titled "Python-Based Renewable Energy Resource Analyser (RERA): A Multi-Criteria Decision Support Tool for Renewable Energy Site Suitability in Namibia." This work highlights his interest in integrating GIS, programming, and multi-criteria analysis to address national development challenges in renewable energy planning.

Contact Information

Jeffrey N.S. Shigwedha
Organisation: Department of Land and Spatial Sciences, Namibia University of Science and Technology (NUST), Namibia
Address: PO Box 98621, Pelican Square, Tauben Glen, Windhoek
City: Windhoek
Country: Namibia
Tel: +264 81 748 4728
Email: jsnshigwedha@gmail.com

Ryan Theodore Benade
Organisation: Department of Land and Spatial Sciences, Namibia University of Science and Technology (NUST), Namibia
City: Windhoek
Country: Namibia
Tel: +264 81 716 5949
Email: rbenade@nust.na

Prof. Oluibukun Ajayi
Organisation: Department of Land and Spatial Sciences, Namibia University of Science and Technology (NUST), Namibia
City: Windhoek
Country: Namibia
Tel: +264 61 207 2961
Email: oajayi@nust.na