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GIS software applications in wind energy: emerging technological landscape

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ABSTRACT

Geographic Information Systems (GIS) are tools for managing, analyzing, and visualizing spatial data by integrating environmental, social, and technical variables to support territorial understanding and decision-making. Renewable energies, such as solar, wind, hydro, geothermal, and biomass, are vital for reducing carbon emissions and promoting sustainability. Among them, wind energy stands out for harnessing wind power to generate electricity, becoming a key driver of the global energy transition. This study conducts technological analysis by using a technology selection framework comparing GIS software applications and technologies applied to wind energy, observing behavioral in maturity, integration, performance, and interoperability. Also, it allows for identifying emerging tools with high potential to strengthen geoscientific and technological knowledge of non-conventional energy sources.

Keywords: Geographic Information Systems, Software Application, Renewable Energies, Technology selection framework, Wind Energy.

INTRODUCTION

Geographic Information Systems (GIS) are tools for the analysis, management, and cartographic representation of spatial information, an alternative for articulating environmental, technical, social, political, and economic variables; this leads to an understanding of the behavior of the territory and enables decisions to be made based on spatial evidence and multi-criteria analysis (Xu et al., 2025). GIS software applications are computer programs that perform the central functions of GIS, such as data compilation, storage, querying, analysis, and visualization, thus aiding the solution of a wide range of discipline-specific geographic problems, including assessing energy resources, and land-use planning (Mençik et al., 2022). These systems allow the integration of geospatial information with energy models in order to study the potential of renewable energy sources and improve land use planning by simulating scenarios that include technical, economic, and environmental aspects.

Renewable energies, including solar, wind, hydro, geothermal, and biomass, are one of the main pillars for advancing toward energy sustainability and meeting the Sustainable Development Goals (SDG), especially the SDG 7: "Affordable and Clean Energy," which seeks universal access to quality, affordable, and secure energy, as these energies contribute to reducing emissions and promoting environmental sustainability. This is part of the transition to a decarbonized energy model, a process through which greenhouse gas emissions are progressively reduced by replacing fossil fuels with renewable energies and promoting complementary technologies (Moreda Meleiro, 2023).

Accordingly, wind energy, which is classified as a renewable energy source, has one of the highest generation potentials, the largest available territory, and is experiencing the fastest growth globally. The progress of this energy has been driven by advances in digital technologies and trends. According to Das et al. (2025), the development of wind energy has been favored by the application of spatial analysis and predictive simulation technologies.

Some studies have been conducted to observe digital and software tools in the renewable energy sector: Pérez-Illidge et al. (2021) present an approach to technology watch in residential solar photovoltaic (solar panel) companies in the department of La Guajira in Colombia. For their part, Feo Duitama, and Archila (2025) propose technology watch and competitive intelligence for the development of energy innovation projects for the densification of residual biomass. In addition, Xu et al. (2025) present a study that combines GIS with the energy simulation model called "EnergyPlan" to improve electrical planning capabilities, demands, and potential in geospatial analysis and aspects of energy access. Similarly, Das et al. (2025) present a hybrid approach for site selection and energy resource estimation in decentralized off-grid hybrid systems, which considers both GIS and multi-criteria decision-making techniques. However, they lack a way to select technologies for GIS software applications.

Consequently, this paper presents a study of GIS software applications in wind energy, aimed at reviewing the emerging technological landscape using a software selection framework, which is a process of searching, analyzing, and evaluating strategic information on innovations, trends, and technological developments. Such a methodology guides the analysis of existing GIS software applications and the identification of emerging technologies, which can support the development of future GIS applications for wind energy (Feo Duitama & Archila, 2025; Observatorio Tecnológico de la Universidad de Alicante, n.d.). Monitoring allows for the identification of both differences and convergences in the dimensions that structure these tools (environmental, technical, socioeconomic, and legal), in addition to evaluating their infrastructure, usability, and interoperability. Additionally, the inclusion of applied technology selection framework through proof-of-concept testing allows validation of the actual performance of these systems in response to specific wind project requirements, thus providing practical evidence to reinforce the comparative analysis.

The growing global demand for renewable energy and the need for efficient management of wind resources justify the importance of studying GIS software applications in this field. The rapid technological evolution of these tools requires continuous assessment to understand their capabilities, maturity, and potential contribution to sustainable energy development. By applying a technology surveillance approach, this study provides a structured and evidence-based analysis that helps identify trends, gaps, and opportunities in the use of GIS technologies for wind energy applications, contributing to the advancement of both research and practical implementation in the sector (Monsalve Ospina & Castro Álvarez, 2022).

The structure of this paper is organized as follows: in the section II is described the methodology for guiding the development of the study; subsequently, in section III, the background is related to GIS software applications in wind energy identified during the information search is presented. Then, the results are presented in section IV corresponding to the emerging technological landscape, and its comparative analysis is discussed. Finally, the paper addresses the discussions on the identified technological gaps, research and transfer opportunities in section V, and the conclusions derived from the study are included in section VI.

METHODOLOGY

The methodology is structured as a technology selection framework for software projects in energy fields, integrating phases of the technology surveillance (Feo Duitama & Archila, 2025; Observatorio Tecnológico de la Universidad de Alicante, n.d.) with technological review and practical proof of concept validations to the identification, analysis, and evaluation of relevant information for decision-making. The study is developed in three stages as is described in **Figure 1**.

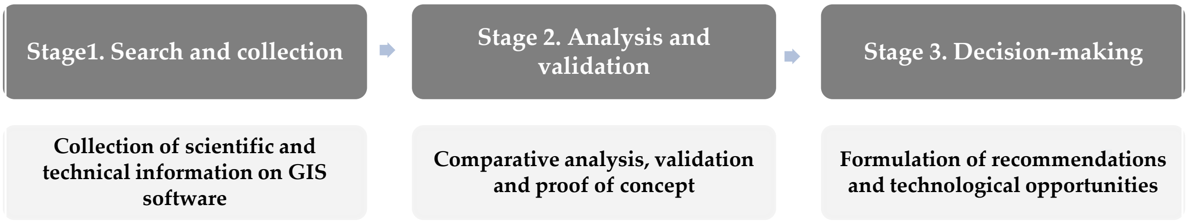

Figure 1. Stages of technology selection framework

Stage 1. Search and collection

A data collection strategy was developed through the identification of relevant keywords and technological sources related to GIS software applications in wind energy. The search included scientific publications, technical reports, software documentation, institutional geoportals, and vendor websites.

Keywords included combinations of "GIS", "GIS platform", "GIS software application", "wind energy assessment", "wind energy software", "renewable energy mapping", and "technology related to GIS".

Ensuring a systematic characterization of the technological landscape, GIS software applications were selected according to the inclusion and exclusion criteria presented in **Table 1**. The selected applications were analyzed in terms of their application domains and the technologies used in their implementation. This characterization enabled the identification of recurring technological components, platforms, and software ecosystems supporting current GIS software applications in the energy sector.

Table 1. Inclusion and exclusion criteria for GIS software application selection.

Category	Criteria
Inclusion	Applications related to renewable energy or wind energy processes
Inclusion	Applications incorporating GIS capabilities for spatial analysis, visualization, or decision support
Inclusion	Applications addressing environmental, technical, socioeconomic, legal, or territorial dimensions
Inclusion	Applications with publicly available technical documentation
Inclusion	Applications providing information about the technologies, platforms, or software components used
Exclusion	Applications without GIS functionality
Exclusion	Applications not related to energy applications
Exclusion	Applications lacking sufficient technical documentation
Exclusion	Applications providing redundant information

Stage 2. Analysis and validation

The information collected during the search phase was analyzed to characterize the current landscape of GIS software applications in wind energy and to identify the technologies supporting their development. The selected applications were examined according to their application domains and technological components, enabling the identification of recurring technologies, architectures, and software ecosystems. To evaluate the suitability of such technologies for the development of future GIS software applications, a Proof of Concept (PoC) was implemented using a geospatial workflow for wind energy analysis.

The evaluation of the technologies identified during the PoC process is guided by the following criteria: (i) *maturity* refers to the degree of technological development and readiness for adoption; (ii) *integration* evaluates how effectively different components operate together within unified workflows; (iii) *performance* refers to the efficiency with which a system carries out processing tasks, typically evaluated using metrics to quantify speed, resource utilization, and overall processing behavior, and (iv) *interoperability* concerns the ability of heterogeneous tools to exchange and use geospatial information through shared standards (Das et al., 2025). This process provided practical evidence regarding their capability to support geospatial data processing, visualization, system integration, and decision-support functionalities within GIS environments to enable comparison among technologies, each criterion was assessed using a five-level scale ranging from 1 (Very Low) to 5 (Very High). The assessment considered documentation availability, compatibility with geospatial workflows, execution behavior observed during the PoC, and support for standard geospatial formats and services.

Stage 3. Decision-making

The findings obtained from the analysis and validation stages were interpreted to identify technological trends, gaps, and opportunities associated with GIS applications in wind energy. This stage focused on examining the implications of the identified technologies and their potential contribution to the development of future GIS solutions capable of integrating environmental, technical, socioeconomic, legal, and territorial dimensions. The outcomes of this phase support the discussion of the current technological landscape and provide the basis for recommendations regarding technology adoption, future research directions, and opportunities for knowledge transfer in the wind energy sector.

BACKGROUND ON GIS SOFTWARE APPLICATIONS IN WIND ENERGY

Global Level

Globally, GIS are used for wind resource analysis. General-purpose GIS platforms support spatial data management; multicriteria evaluation, and visualization of wind potential are described in **Table 2** (CUHK Library, n.d.; Mapline, 2025; MappingGIS, 2022). GIS software applications are used for integrating GIS functions with energy modeling modules to simulate wind flow, optimize turbine layouts, and calculate energy yield and wake effects, which are described in **Table 3** (Karataş & Bıçakcı, 2025; Amsharuk & Łaska, 2023; Kamdar et al., 2021).

Table 2. Global level GIS technologies

GIS	Description
WindPRO	GIS for wind-farm planning; wind analysis, noise, shadow, and annual energy production. Developer: EMD International A/S. Sitehttps://www.emd-international.com/software/windpro
ArcGIS/ ArcGIS pro	Multicriteria spatial analysis and 3D mapping, management of wind-site data. Developer: Esri, Site: https://www.arcgis.com/index.html
Google Earth Engine	Cloud-native geospatial analysis for large-scale environmental and climate datasets. Developer: Google. Site: https://earthengine.google.com/
QGIS	Open source for spatial data visualization, editing and analysis; supports renewable energy mapping. Developer: QGIS. Site: https://qgis.org/
Grass GIS	Open source in raster processing, terrain modeling, and environmental simulations; suitable for wind and topographic analysis. Developer: OSGeo. Site: https://grass.osgeo.org/
Saga GIS	Free GIS focused on terrain, hydrological, and surface analysis; often used for slope and landform modeling. Developer: University of Hamburg (SAGA GIS Development Team). Site: https://saga-gis.sourceforge.io

Table 3. Global level GIS software applications

GIS software application	Description	Dimension	Technologies
WAsP	Wind Atlas Analysis and Application Program for wind-resource assessment, micro-siting, and energy-production estimation. Developer: DTU Wind and Energy Systems. Site: https://wasp.dtu.dk	• Technical • Environmental	Native Python API (PyWAsP), imports diagram libraries (NumPy, GeoPandas, GDAL, Rasterio). Integrates with QGIS (scripting plugins) and ArcGIS. Cloud data layers with Google Earth Engine.
WindFarmer	Tool for layout design, wake-loss modeling, and energy-yield optimization. Developer: DNV. Site: https://www.dnv.com/software/services/windfarmer/	• Technical • Economic • Environmental	Python for Web API integrations, uses NumPy for matrix operations and GitHub for SDK automations.
WindSim	CFD-based simulation of wind flow in complex terrain. Developer: UL Solutions. Site: https://windsim.com/	• Technical • Environmental	C++/Fortran (PHOENICS engine). ArcGIS integration, AWS (Cloud), NumPy, and GeoPandas for data exports and automation.
OpenWind	Optimization of turbine layout to maximize annual energy Production (AEP) and reduce wake losses. Developer: WindSim AS. Site: https://www.ul.com/software/openwind-wind-farm-modeling-and-layout-design-software	• Technical • Environmental • Economic	Native GIS-centric C++ desktop core. Integrates and processes spatial data with ArcGIS, Python, NumPy, with code management via GitHub.
WindGIS	Cloud-based GIS system, which centralizes data and enhances team collaboration in the offshore wind industry. Developer: Lautec, Site: https://lautec.com/discover-WindGiS/	• Technical • Environmental	Integrates ArcGIS Enterprise, AWS (Cloud), and processes diagram file formats (Shapefiles, GeoJSON, CSV).
RETScreen Expert	Technical evaluation and emission feasibility for renewable projects. Developer: Natural Resources Canada. Site: https://natural-resources.canada.ca/maps-tools-publications/tools-applications/retscreen	• Technical • Economic • Environmental	Integrates ArcGIS (GIS Software map layers) and connects directly with AWS (Cloud) to stream climate data.

Such GIS software applications for wind energy present some limitations: applications focus primarily on technical and environmental analyses—such as wind flow modeling, resource assessment, and wake simulations, while socio-economic, legal, and planning constraints are often addressed separately using external datasets or independent decision-support tools. As a result, such platforms lack integration of the technical, environmental, legal, social, and economic dimensions required for comprehensive wind farm planning and siting (Karataş & Bıçakcı, 2025; Amsharuk & Łaska, 2023; Kamdar et al., 2021). GIS-related patents are associated with the development of spatial data infrastructure technologies, particularly Open geospatial Consortium services (processing of geospatial data and datasets), cloud-based GIS, and emerging collaborative approaches such as volunteered geographic information and crowdsourcing (Rubi & Boscan, 2020).

National Level (Colombia)

In the national context of Colombia, the focus is on institutional geoportals and information systems developed by key government entities, such as the Agustín Codazzi Geographic Institute (IGAC), the Colombian government entity responsible for official mapping, national cartography, and land registry management for territorial planning (Instituto Geográfico Agustín Codazzi, n.d.) and the Mining and Energy Planning Unit (UPME), a national special administrative unit linked to the Colombian Ministry of Mines and Energy, responsible for the ongoing, indicative, and comprehensive planning of the development and use of energy and mining resources (Unidad de Planeación Minero-Energética, n.d.). Such applications, detailed in **Table 4**, are geared toward consulting and viewing official geospatial data, providing fundamental information on land use, topography, infrastructure, and, crucially, the country energy and mining resources. Such national platforms are based on ArcGIS technology.

However, such GIS software applications provide official territorial information, they are primarily designed for consulting and viewing data, without including social, community, or institutional factors in analytical processes that facilitate decision-making with multi-criteria analysis models that combine social, technical, economic, and environmental aspects. Site selection requires multi-criteria decision-making procedures in advanced GIS systems, which make it possible to weigh various constraints and criteria (Yousefi et al., 2022). Likewise, in Colombia, some wind projects have suffered delays or stoppages due to territorial conflicts, incomplete prior consultation processes, and mistrust between developers and local communities, e.g., Guajira projects, since, creation of wind farms causes tensions by perceived effects on the landscape, limitations on traditional land use, and inappropriate community participation methods (Medina Carreño, 2024; Soto Gutiérrez, 2016). Furthermore, studies on equitable energy transition in Colombia emphasize the lack meaningful participation, failure to engage in dialogue with local actors, and insufficient integration of territorial dynamics generate conflicts and resistance that directly impact the regional implementation of energy projects (Hurtado Ramírez, 2023; Ministerio de Minas y Energía, 2024).

Table 4. National level GIS software applications

GIS software application	Description	Dimension	Technologies
IGAC Geoportal	Land use, topography, and natural resources. Client–server web platform. Site: https://geoportal.igac.gov.co/	• Technical • Environmental • Legal	Integrates ArcGIS, scales via AWS (Cloud), utilizes JavaScript (via ArcGIS API) paired with REST/Web Services, and exports vector formats (Shapefiles, GeoJSON).
Colombia en Mapas	Land use, infrastructure, renewable energy data, Architecture with REST services. Site: https://www.colombiaenmapas.gov.co/	• Technical • Environmental	Native deployment on ArcGIS Server paired with cloud scalability via AWS.
SIMEC (UPME)	Energy-mining information system. Web platform with open data modules. Site: https://www.upme.gov.co/simec/geovisores	• Technical • Economic	Integrates ArcGIS, deploys REST/Web services for open dashboards
Sectoral Geoportal - GPS (UPME)	Viewers for energy and mining sector geospatial data, including generation, transmission, and renewable resources. Site: https://sig.upme.gov.co/portal/apps/sites/#/geoportal-sectorial-gps	• Technical • Environmental • Economic	ArcGIS Enterprise (GIS Software), scales over AWS (Cloud), and processes map formats.
ICDE Geovisor	National geographic viewers offer maps and services for territorial, environmental, and energy analysis. Site: https://www.icde.gov.co/geovisor	• Technical • Environmental	Built on ArcGIS (GIS Software), consumes decentralized GeoServer feeds via WMS/WFS Web Services.

Regional Level (Antioquia)

The analysis focuses on the Department of Antioquia is listed in **Table 5**. Such GIS software applications are developed by real-time environmental monitoring systems (SIATA), the regional science and technology program that monitors environmental, hydrometeorological, and air quality variables in real time in Medellín and Valle de Aburrá (Sistema de Alerta Temprana de Medellín y el Valle de Aburrá, n.d.) and environmental management portals (Corantioquia), a public organization, which is responsible for managing natural resources and the environment in the center of the department of Antioquia (Corporación Autónoma Regional del Centro de Antioquia, n.d.) to urban data visualizers (GeoMedellín), an official portal that brings together geographic, urban, and territorial information at Medellín for consultation, downloading, and viewing of open data (Alcaldía de Medellín, n.d.).

Table 5. Regional level GIS software applications

GIS software application	Description	Dimension	Technologies
SIATA	Real-time monitoring of environmental variables and risk alerts using IoT sensors and meteorological stations. Site: https://siata.gov.co/	• Technical • Environmental	Built on Python backend via DjangoREST/Flask utilizing NumPy and GeoPandas (Libraries). Integrates React (Frontend), PostgreSQL/PostGIS (Databases), and manages development via GitHub (DevOps).
Corantioquia GIS System	Environmental GIS portal for protected areas, hydrology, soils, and land zoning. ArcGIS-based client–server architecture. Site: https://www.corantioquia.gov.co/sistema-de-informacion-geografico-de-corantioquia	• Environmental • Legal	Built natively on ArcGIS Server / MapServer (GIS Software), exposes geographic attributes via REST/Web Services with JavaScript, and downloads spatial vector datasets (Shapefiles).
GeoMedellín	Official geographic viewer of Medellín for interactive consultation on territorial and urban data. ArcGIS Server infrastructure. Site: https://www.medellin.gov.co/geomedellin	• Technical • Social • Environmental	Built on ArcGIS Enterprise and ArcGIS Hub (GIS Software), uses JavaScript and Python as programming languages.
Área Metropolitana Open Data Portal	Official portal centralizing open datasets of the metropolitan area. Site: https://datosabiertos.metropol.gov.co/	• Technical • Social • Environmental	Deployed on ArcGIS Hub framework (GIS Software) utilizing front-end JavaScript mechanics.
GeoDatos-Government of Antioquia	Aggregates maps and data from departmental agencies for public territorial information. Site: https://gobantioquia.maps.arcgis.com/apps/webappviewer/index.html?id=e7909ee1328b455e96a862dd28c6de0d	• Technical • Social	Built on ArcGIS Hub / Web AppBuilder, utilizes JavaScript engines, streams data using REST/Web Services.

Such applications are based on ArcGIS platforms. However, such GIS software applications in Antioquia are dedicated to environmental monitoring and territorial data consultation; they do not focus on the development of wind energy projects, nor do they provide viability analyses or integrate social, community, and territorial dimensions that are essential for assessing the feasibility of such initiatives.

RESULTS

The analysis of the GIS software applications presented in **Tables 2** and **3** revealed a set of recurring technological components that support the implementation of geospatial solutions for wind energy. By examining the technologies reported in the selected applications, common patterns were identified across geospatial processing environments, visualization frameworks, backend services, spatial databases, and cloud-based architectures. Such technologies enable interoperability, remote processing, and scalable analytical workflows (Mençik et al., 2022). Furthermore, the reviewed applications showed modern GIS solutions rely on complementary technologies extending the capabilities of traditional GIS platforms. Based on such findings, the emerging technological ecosystem identified in the study is synthesized in **Figure 2**.

Among the recurrent technologies are programming environments such as *Python*, adopted open-source language for geospatial development. Its ecosystem includes libraries such as *GeoPandas* (for handling vector geospatial data) and *Shapely* (which enable sophisticated geometric and vector operations) (Rey et al., 2023; Padgham et al., 2019). GDAL (Geospatial Data Abstraction Library) and Rasterio (both for raster information management and geospatial data) (MappingGIS, 2022; Rasterio Development Team, n.d.). Additional components such as *NumPy* (which supports fast numerical operations on data structures), *Pandas* (complement NumPy with data structures to process statistical results) and *Matplotlib* (used as a visualization library for plots, charts for geospatial datasets). Such technologies are components of reproducible workflows in geospatial analysis (Lemenkova, 2020).

The ecosystem is further complemented by web visualization technologies, including *Folium* (for interactive web mapping) and *Kepler.gl* (for interactive exploration of large datasets) (Wu, 2021). Similarly, backend frameworks support the development of geospatial services, such as *FastAPI* (high-performance Python framework for data-driven apps), *Flask* (lightweight Python web framework), and *Django* (full-stack Python web framework for scalable web apps), used to expose spatial data to web clients within practical client-server architectures (Čižmár, n.d.). Therefore, such ecosystem connects to spatial databases such as *PostgreSQL* (open-source object-relational database management system) with *PostGIS* (spatial extension of PostgreSQL with GIS supported data types), providing adopted open-source spatial support for GIS and web mapping (MappingGIS, 2022), cloud architecture, and establishing a hybrid environment. Additionally, such ecosystem enables versatile and scalable spatial analysis, complementing traditional GIS platforms and specialized wind energy tools, which continue to play a role in data management, spatial processing, and domain specific analytical functions.

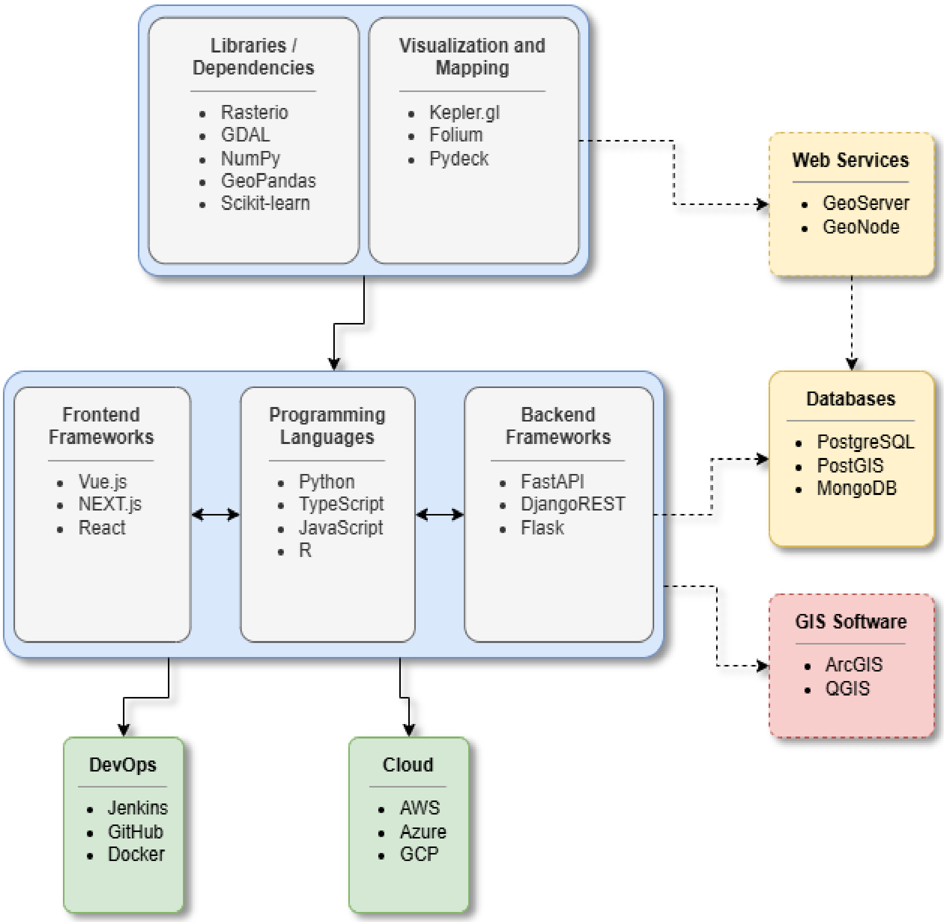

Figure 2. Summary of Technologies

To assess the suitability of the identified technologies for GIS software development in wind energy, a validation process was conducted by using a PoC. The PoC implemented a reproducible workflow for calculating a Wind Suitability Index (WSI) using spatial analysis techniques. The identified technologies were evaluated according to four criteria: maturity, integration, performance, and interoperability. Each criterion was assessed using a five-level scale ranging from 1 (Very Low) to 5 (Very High), enabling a comparative analysis of the technologies within a controlled development environment. The results of this assessment are presented in **Table 6.** The PoC can be acceded by using following link.

Table 6. Assessment of emerging technologies identified for GIS software application development in wind energy

Libraries	Maturity	Integration	Performance	Interoperability
Python, NumPy, Pandas	(5) Stable and documented ecosystems.	(5) Integrates raster, vector, and analytical workflows.	(5) Efficient numerical and tabular processing.	(4) Compatible with standard data structures used across geospatial libraries.
Shapely, GeoPandas	(5) Well-established for vector-based spatial analysis.	(5) Raster processing and configuration-driven workflows.	(4) Adequate efficiency for medium-scale spatial operations.	(5) Support standard vector formats for desktop GIS and web environments.
Rasterio	(5) Stable library built on GDAL used for raster analysis.	(5) Enables combined raster–vector processing within the PoC.	(5) Contributes to a total execution time of approximately 1.02 s.	(5) Produces outputs compatible with conventional GIS platforms.
Folium, Matplotlib	(4) Mature visualization tools with extensive community use.	(4) Consume outputs generated by analytical components.	(4) Introduce limited computational overhead during map generation.	(4) Generate web-ready outputs for interactive and static visualization.
psutil	(5) Established system-monitoring library.	(4) Integrated as a supporting component within the workflow.	(5) Enables measurement of execution time and memory usage (128.5 MB).	(3) Exports metrics in standard formats suitable for external analysis.

DISCUSSION

While global GIS tools offer advanced technical capabilities such as wind flow modeling and wake simulation, national and regional platforms in Colombia remain primarily descriptive and generally lack integrated multi-criteria analysis capabilities. This gap highlights the need for unified GIS environments capable of evaluating territories through multiple dimensions, including technical, social, economic, legal, and environmental factors.

Rather than relying on isolated proprietary systems or simple data viewers, the integration of complementary technologies—including spatial databases, geospatial processing libraries, and modern web frameworks—enables a more comprehensive approach to spatial decision-making. The analysis of the reviewed applications revealed recurring technological components that constitute the foundation of contemporary GIS development environments.

Furthermore, the validation results obtained by using the PoC indicate high levels of maturity, integration, performance, and interoperability for development technologies for GIS software applications in wind energy. In particular, the results suggest integrated open-source ecosystems can execute complex spatial workflows efficiently while maintaining compatibility with standard geospatial formats and services. Such findings suggest technologies identified could provide a foundation for developing decision-support systems that better integrate engineering assessments with local territorial constraints and stakeholder requirements.

Consequently, the examination of the current GIS landscape reveals several limitations in how existing systems address multi-dimensional decision-making processes, as discussed below.

Identified Technological Gaps

Current GIS software applications for wind energy focus on technical and environmental variables, while socioeconomic, legal, and territorial dimensions are often treated as external considerations rather than integrated analytical components. Globally, specialized platforms such as WAsP, WindSim, WindFarmer, and WindPRO provide advanced capabilities for wind resource assessment, wind flow modeling, and wake-effect simulations. However, such tools are primarily designed to support engineering analyses and offer limited mechanisms for incorporating social, community, legal, or territorial factors into their decision-making processes. As a result, technical evaluations are conducted independently of the local realities and stakeholder conditions that may ultimately influence project feasibility.

Within the Colombian context, institutional and regional geoportals managed by organizations such as IGAC, UPME, and governmental entities are primarily oriented toward the consultation and visualization of official geospatial information. Although these platforms provide valuable territorial and environmental datasets, they generally lack integrated multi-criteria analysis capabilities. In addition, many of these platforms exhibit similar functionalities and are mainly designed as descriptive information systems rather than analytical decision-support environments. Consequently, they provide limited support for evaluating complex interactions among technical, environmental, social, legal, and territorial variables.

The analysis of the reviewed applications revealed that most existing solutions address specific stages of the planning process but rarely provide a unified framework capable of integrating multiple project dimensions. This fragmentation creates a technological gap between engineering-oriented assessments and broader territorial decision-making requirements. As renewable energy projects become increasingly dependent on social acceptance, regulatory compliance, and environmental sustainability, the need for multidimensional analytical environments becomes more evident.

The emerging technological ecosystem identified in **Figure 2** suggests a possible pathway to address these limitations. The recurring use of geospatial processing libraries, spatial databases, web-based GIS frameworks, and cloud-enabled architectures demonstrates a shift toward modular and interoperable software environments. Furthermore, the validation results presented in **Table 6** indicate that these technologies achieve high levels of maturity, integration, performance, and interoperability. The PoC demonstrated that integrated open-source ecosystems are capable of executing complex spatial workflows efficiently while maintaining compatibility with standard geospatial formats and services.

Therefore, there is a need to move beyond isolated software tools and descriptive geoportals toward hybrid GIS ecosystems capable of supporting real-time processing and multi-criteria decision-making. Such environments would enable technical, environmental, socioeconomic, legal, and territorial variables to be analyzed simultaneously within a unified framework, improving the ability of decision-makers to assess project feasibility, identify potential conflicts, and support more sustainable wind energy development strategies.

CONCLUSIONS

Results demonstrated that Python-based tools and libraries integrated with ArcGIS provide reproducible environments for wind energy projects. The study concludes that the integration of cloud-native geospatial architectures and decentralized processing is no longer optional but a requirement for real-time wind resource management. The identified Python libraries (GeoPandas, Rasterio, and Folium) demonstrated a high degree of maturity and performance, reaching a total execution time of approximately 1.02 s in simulated environments.

Beyond technical performance, the viability of wind energy in Colombia is inextricably linked to territorial legitimacy. GIS software applications must evolve from simple data viewers into collaborative decision-support systems that incorporate social dynamics and community dimensions as core variables. This transition from primarily environmental and technical analyses toward comprehensive territorial management platforms will be vital in mitigating the conflicts and delays currently hindering the national energy transition.

The technological mapping revealed a differentiated landscape across the global, national, and regional levels. Global applications combine specialized wind energy software with GIS platforms, programming environments, geospatial libraries, cloud services, and automation tools. In contrast, Colombian national and regional applications rely more strongly on ArcGIS-based architectures, web services, and institutional geoportals for the publication and consultation of territorial information. These findings show that current GIS applications are not supported by a single technology, but by interconnected ecosystems composed of GIS software, analytical libraries, databases, web services, cloud infrastructure, and development tools.

The main technological gap identified is therefore not the absence of geospatial technologies, but the fragmentation between specialized energy modeling, institutional data infrastructures, and multidimensional territorial assessment. Specialized global applications provide advanced capabilities for wind-resource estimation, layout optimization, and energy-yield analysis, while national and regional platforms provide authoritative environmental, geographic, and territorial data. However, these capabilities are rarely integrated within a unified workflow. Strengthening interoperability among these components would allow existing technological resources to be combined more effectively and would support the incorporation of technical, environmental, economic, social, and legal dimensions into renewable-energy planning.

Within this context, the technology selection framework provides a structured basis for determining how different technological components can complement one another according to their maturity, integration, performance, and interoperability. Rather than promoting the replacement of existing institutional platforms, the framework supports the identification of suitable combinations between established GIS infrastructures and emerging analytical, web, database, and cloud technologies. This approach can guide architectural decisions, technology investment, and knowledge-transfer strategies for the development of more integrated GIS applications in wind energy and other renewable energy fields.

Future research should focus on the formalization of a comprehensive development framework for standardizing the integration of this technology selection methodology within the lifecycle of renewable energy projects. Such a framework must go beyond technical evaluation to establish a systematic protocol for aligning emerging geospatial technologies with evolving regulatory and social requirements. Investigating how this methodology can be embedded into institutional decision-making processes will be essential to ensure that the selection of GIS software applications remains consistent, transparent, and adaptable to the specific territorial complexities of the global energy transition. While this study focuses on wind energy, the proposed technology selection framework remains applicable to other renewable energy fields.

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DECLARATIONS OF CONFLICT OF INTEREST AND AUTHORS

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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