Application of Remote Sensing and Geographic Information Systems in Identifying and Evaluating Renewable Energy Resources

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***Abstract*—Renewable energy sources have gained attention in recent decades because fossil fuel resources are depleting and global population growth has increased energy demand. This study reviews how remote sensing and Geographic Information Systems (GIS) are used to identify and evaluate renewable energy sources, such as solar, wind, hydroelectric, biomass, and geothermal energy. This paper is to show the application of GIS techniques and remote sensing to identify optimal locations for harnessing these resources. The results show that combining remote sensing and GIS is more efficient than using either technology alone. This article also analyzes current and future challenges in applying these technologies and proposes potential solutions. The findings and recommendations of this study can be useful for researchers and policymakers in the field of renewable energy.**

Keywords—Renewable energy, remote sensing, Geographic Information Systems (GIS), solar energy, wind energy, hydroelectric energy, biomass, geothermal energy

I. Introduction

The world today faces numerous challenges in the energy sector. This leads modern countries to invest on renewable energy sources. Fossil fuels, such as oil, natural gas, and coal, which have been the primary energy sources for electricity generation, transportation, and industries for decades, are not only running out but also produce greenhouse gas emissions that pose a serious threat to the environment [1]. According to international reports, continuing to rely on these resources at the current rate could lead to catastrophic consequences for global ecosystems . As a result, renewable energy sources have gained attention as sustainable and clean alternatives [2]. These sources can meet the energy needs of modern societies and also help reduce carbon emissions, thereby improving environmental quality .

Renewable energy sources have unique characteristics that make them attractive options for the future of energy. It is regarded as a clean energy technology that significantly participates in energy development and developing countries progress [3], [4]. For instance, solar energy harnesses the sun's abundant radiation, and advancements in photovoltaic technology have significantly reduced its production costs [5]. Wind energy has also seen rapid growth, particularly with the installation of wind turbines in coastal and offshore areas in countries like China and Denmark, which has made it one of the fastest-growing energy sources [6], [7]. Hydroelectric energy, with its long history of clean electricity production, remains one of the most reliable renewable sources, although selecting suitable locations for hydroelectric plants requires careful assessment of environmental impacts [8]. Biomass, which is derived from organic materials like agricultural and forestry residues, plays a significant role in energy supply, particularly in developing countries [9]. Finally, geothermal energy, which utilizes the Earth's natural heat, offers a sustainable option with high potential for electricity and heating applications.

However, effectively harnessing these resources requires precise identification of optimal locations and evaluation of their potential. Remote sensing and Geographic Information Systems (GIS) have emerged as key tools in renewable energy studies. Remote sensing provides accurate data on land surfaces, weather patterns, and geographical features, which enables rapid and extensive analysis of various regions [10]. For example, satellite imagery and LiDAR data are crucial for identifying suitable locations for wind turbines or solar panels [11]. Meanwhile, GIS integrates spatial and non-spatial data, which facilitates multidimensional analysis of energy resources and supports informed decision-making [12]. These technologies are particularly effective for assessing renewable energy potential on a large scale or in remote areas, where traditional field surveys are time-consuming and costly .

The use of remote sensing and GIS in renewable energy studies is not limited to identifying suitable locations but also extends to project management and optimization. For instance, in wind energy projects, remote sensing data can analyze wind speed and direction at different altitudes, while GIS enables the evaluation of environmental factors like topography, land use, and proximity to infrastructure. In solar energy projects, remote sensing assesses solar radiation intensity and the impact of obstacles like clouds or shadows, while GIS supports the spatial analysis of these resources .

For biomass, these technologies estimate the availability of organic materials and optimize supply chains and transportation. In hydroelectric projects, remote sensing and GIS are critical for analyzing watersheds, water flow patterns, and environmental impacts. For geothermal energy, these tools help identify areas with high thermal potential and assess subsurface resources [13]. Figure 1 shows a combination of remote sensing and ANN for renewable energy forecasting.

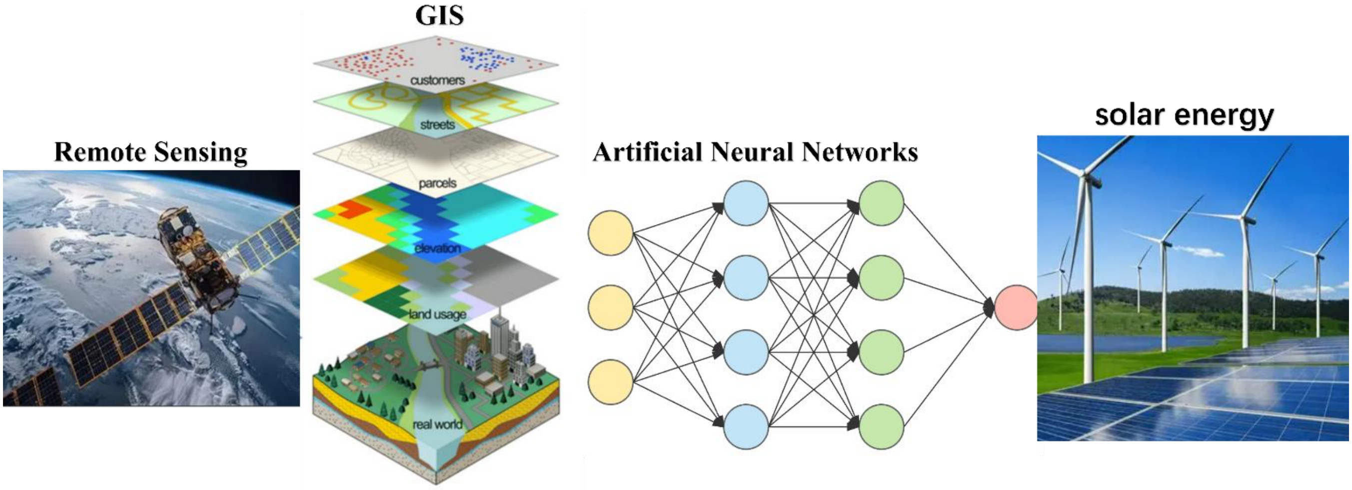

Figure 1. Combination of remote sensing and ANN for renewable energy forecasting.

Despite significant advancements in the use of these technologies, challenges remain. Limitations such as high initial setup costs, the need for high-quality data and expertise in data analysis, and complexities in integrating multi-source data are among the obstacles that need attention. Additionally, the environmental and social impacts of renewable energy projects, particularly hydroelectric plants and offshore wind farms, require more thorough assessments using these technologies. However, recent advancements in image processing algorithms, artificial intelligence, and machine learning have enhanced the ability of these tools to analyze complex data and provide innovative solutions .

This article firstly examines conventional methods and their limitations in identifying, evaluating, and managing renewable energy resources. Then to improve the exploration and utilization of them, geospatial analysis which uses remote sensing and GIS is discussed. In order to support the finding, some real case studies are analyzed. Finally, the article analyzes future challenges and opportunities in this field and offers recommendations for policymakers and researchers. This study can serve as a valuable resource for developing sustainable strategies in the renewable energy sector.

II. Data

To investigate the applications of geospatial analysis, a structured methodology was designed, which includes literature review, selection of case studies, and data analysis. This study focuses on solar, biomass, hydroelectric, wind, and geothermal energy. The objective is to identify the methods used for exploring and assessing these resources, as well as to examine their limitations and opportunities.

A. Conventional Methods in Renewable Energy Exploration

Conventional methods for exploring renewable energy resources involve field surveys and manual analyses, which are often time-consuming and limited to small scales. For example, in geothermal energy exploration, the process includes initial identification, exploration, drilling, and resource analysis . Traditional methods, such as hydrogeological, geochemical, and geophysical surveys (seismic, gravimetric, and electrical resistivity), are employed. These methods are described by the following equations:

- **Seismic surveying**: The seismic wave velocity is calculated using the equation $v = \sqrt{(E/\rho)}$, where E is Young's modulus and ρ is rock density [42].
- **Gravimetric surveying**: Variations in the gravitational field are analyzed with the equation $\Delta g = GM/r^2$, where G is the gravitational constant, M is mass, and r is distance [43].
- **Electrical resistivity**: Specific resistivity is measured using $\rho = RA/L$, where R is resistance, A is the cross-sectional area, and L is length.

In wind energy, meteorological masts measure wind speed, which is limited by location constraints . For solar energy, radiation intensity is calculated using local instruments and the equation $I = I_0 \cos(\theta)$, where I_0 is the initial radiation intensity and θ is the angle of incidence. For biomass, field surveys are insufficient for estimating organic resources. In hydroelectric energy, traditional hydrological analyses use the continuity equation $Q = A \cdot v$, where Q is discharge, A is the flow cross-sectional area, and v is flow velocity [14].

B. Applications of Remote Sensing and GIS

Remote sensing employs technologies like satellite imagery, LiDAR, SAR, and SODAR, which provide precise spatial data. The specific applications for each energy type are described below:

- **Geothermal energy**: Satellite thermal imagery (e.g., ASTER) is used to identify thermal anomalies. The heat transfer equation $q = -k\nabla T$, where q is heat flux, k is thermal conductivity, and ∇T is the temperature gradient, is applied to analyze heat flow [15].
- **Wind energy**: LiDAR and SAR data analyze wind speed at various altitudes using the wind power equation $P = 1/2\ \rho A v^3$, where ρ is air density, A is rotor area, and v is wind speed.

- **Solar energy**: Solar radiation intensity is assessed using satellite data and the equation $G = G_0 e^{(-\tau)}$, where G_0 is extraterrestrial radiation and τ is atmospheric turbidity.

- **Biomass**: Landsat imagery estimates vegetation cover and calculates biomass using the model $B = f(NDVI)$, where NDVI is the Normalized Difference Vegetation Index.

- **Hydroelectric energy**: GIS and remote sensing analyze watersheds using the water balance equation $P = Q + E + \Delta S$, where P is precipitation, Q is runoff, E is evaporation, and ΔS is the change in water storage.

C. GIS Techniques

GIS integrates data and performs spatial analyses, such as weighted analysis, multi-criteria modeling, and clustering, to identify optimal locations. For example, in selecting wind farm sites, the weighted equation $S = \Sigma w_i x_i$, where w_i is the criterion weight and x_i is the criterion score, is used. In solar energy, GIS analyzes land slope and radiation with the model $E = G \cdot A \cdot \eta$, where E is the energy produced, G is radiation, A is area, and η is efficiency. For biomass, GIS optimizes transportation costs using the model $C = d \cdot c_u$, where d is distance and c_u is the unit transport cost. In hydroelectric energy, GIS hydrological models assess production potential using the equation $P = \rho g Q h \eta$, where g is gravitational acceleration, h is height, and η is turbine efficiency.

III. GEOSPATIAL ANALYSIS ROLE

Geospatial analysis serves key role in renewable energy sources. These technologies provide accurate spatial data and enable multi-criteria analyses, which overcome the limitations of traditional methods and improve the process of identifying optimal locations for energy projects. This section aims to examine the role of these technologies in various stages of renewable energy exploration and evaluation, with a focus on direct and indirect evidence, specific techniques, and practical applications.

A. Direct and Indirect Evidence in Remote Sensing

Remote sensing data can provide direct or indirect evidence of the potential for renewable energy resources. Direct evidence refers to information that is directly linked to the physical characteristics of an energy source. For instance, in geothermal energy, satellite thermal imagery (e.g., ASTER) identifies surface thermal anomalies, such as hot springs or fumaroles, which are analyzed using the heat transfer equation $q = -k\nabla T$, where q is heat flux, k is thermal conductivity, and ∇T is the temperature gradient. In solar energy, satellite data extract radiation intensity using the equation $G = G_0 e^{(-\tau)}$, where G_0 is extraterrestrial radiation and τ is atmospheric turbidity. Indirect evidence requires more interpretation, such as using vegetation indices (NDVI) to identify heat-stressed areas in geothermal exploration or analyzing wind patterns with SAR data for wind farms. Table 1 summarizes the applications of remote sensing and GIS in exploring renewable energy resources.

Table 1. Applications of Geospatial Analysis in Exploring Renewable Energy Resources

Energy Source	**Remote Sensing Technique**	**GIS Application**	**Direct Evidence**	**Indirect Evidence**
Geothermal	ASTER, HyMap thermal imagery	Fault analysis, reservoir modeling	Hot springs, fumaroles	Stressed vegetation
Wind	LiDAR, SAR, SODAR	Topography analysis, grid proximity	Wind speed and direction	Airflow patterns
Solar	Landsat satellite imagery	Slope and radiation analysis	Solar radiation intensity	Cloud cover, shadows
Biomass	Landsat, Sentinel-2	Land use and transportation analysis	Vegetation cover	Organic resource potential
Hydroelectric	DEM, satellite imagery	Hydrological modeling	River flow	Watershed, topography

IV. METHODOLOGY

Geospatial analysis provides accurate spatial data and enable multi-criteria analyses, which eliminate the limitations of costly and time-consuming traditional field surveys. In geothermal energy, satellite thermal imagery (e.g., ASTER) and hyperspectral HyMap data identify thermal anomalies and altered minerals, which are analyzed using the heat transfer equation $q = -k\nabla T$. These data, combined with GIS modeling, enhance the accuracy of identifying optimal drilling sites. However, challenges such as the need for high-quality data and limitations in areas with cloud cover persist. In wind energy, technologies like LiDAR and SAR analyze wind speed and direction using the wind power equation $P = 1/2\ \rho A v^3$, where ρ is air density, A is rotor area, and v is wind speed, although atmospheric interference and the need for precise calibration can affect data accuracy.

For solar energy, remote sensing evaluates radiation intensity using the equation $G = G_0 e^{(-\tau)}$, but obstacles like shadows and atmospheric turbidity require advanced GIS analysis. In biomass, the NDVI index, calculated as $NDVI = (NIR - Red)/(NIR + Red)$, estimates organic resources, but ground validation is necessary for accuracy. In hydroelectric energy, GIS hydrological modeling assesses power generation potential using the equation $P = \rho g Q h \eta$, where ρ is water density, g is gravitational acceleration, Q is discharge, h is height, and η is turbine efficiency, although environmental impacts, such as river ecosystem degradation, require special attention. Case studies, such as offshore wind farms in China and solar plants in India, demonstrate the success of these technologies on large scales. However, challenges like initial costs, the need for expertise, and multi-source data integration remain, which can be addressed through technologies like artificial intelligence and machine learning.

The integration of remote sensing and GIS not only improves accuracy and efficiency but also enables the analysis of future scenarios. For example, GIS-based climate change modeling can predict long-term impacts on energy resources. However, effective policies to support investment in these technologies and develop data infrastructure are essential. Collaboration among scientists, policymakers, and industry is also critical to overcoming technical and financial barriers.

V. CONCLUSION

GIS and remote sensing, as advanced tools, are important in exploring and evaluating renewable energy resources. These technologies provide accurate data and large-scale analyses, which enhance the process of identifying optimal locations for solar, wind, hydroelectric, biomass, and geothermal energy. Equations like $P = 1/2 \rho A v^3$ for wind, $G = G_0 e^{(-\tau)}$ for solar, and $P = \rho g Q h \eta$ for hydroelectric energy, combined with GIS modeling, improve analysis accuracy. Global case studies highlight the success of these tools in practical projects. However, challenges such as costs, the need for expertise, and data limitations require attention. Integrating these technologies with artificial intelligence and supportive policies can ensure a more sustainable future. This study emphasizes the importance of combining remote sensing and GIS for renewable energy development and recommends increased investment in data infrastructure and specialist training.

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