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A review of renewable technologies for power generation in the high mountain ecosystem

Franky Cely[1*], Jean Pimiento[2], Fabio González[3], Alonso Retamoso[4], Edgar Niño[5], Ingrid Moreno[6]
[1-6] Electric Engineering, Unidades Tecnológicas de Santander, Colombia

*E-mail: fcely@correo.uts.edu.co

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Abstract

Mountainous areas face challenges such as rugged topography, harsh weather, and limited access to power grids; however, they also offer potential for renewable energy generation, mainly through solar and wind resources. This study aims to evaluate the feasibility of implementing renewable energy systems in these regions and identify the most studied renewable technologies in high mountain contexts using the PRISMA methodology for rigorous literature selection and VOSviewer for bibliometric analysis. Among them, solar photovoltaic and wind energy stand out due to their high potential in these environments. The study analyzes key parameters such as technological efficiency, solar radiation variability, and wind patterns, including technical aspects like minimum wind speeds derived from the Weibull distribution and solar irradiance levels necessary for system design. The results show that the insights obtained from the bibliometric analysis help evaluate the feasibility and performance of renewable energy solutions in complex terrains. In conclusion, the study highlights the most viable technologies for high mountain areas and provides recommendations for their implementation. Although technical and environmental challenges persist, these ecosystems offer significant opportunities for sustainable energy generation. The findings provide guidance for future research and the development of innovative projects in remote, mountainous regions.

Keywords: Renewable energy, High mountain ecosystem, Solar photovoltaic energy, Wind energy, Weibull distribution, PRISMA

1. Introduction

The global transition to sustainable energy sources is one of today's most significant global challenges. According to recent studies, most of the energy consumed worldwide comes from fossil fuels, such as coal, oil, and natural gas. However, the intensive use of these resources has led to their progressive depletion and significant environmental impacts, such as increased greenhouse gas emissions and pollution. This situation has driven the need to move towards energy systems based on renewable sources, which offer a cleaner, sustainable, and safer alternative in the long term [1]. This poses a threat to the depletion of these resources shortly and contributes considerably to climate change. These challenges are compounded by the geographical, social, and economic conditions of millions of people worldwide, especially in rural and mountainous areas, who still lack access to a reliable source of electricity [2].

In the face of these challenges, renewable energies have emerged as a promising alternative to guarantee a sustainable electricity supply [3]. In particular, high mountain areas present geographical and climatic characteristics that make access to the conventional power grid difficult, driving the search for autonomous energy solutions. Steep topography, high altitude, and extreme climatic conditions, such as high wind and solar irradiance variability, make installing conventional energy infrastructures challenging, increasing their associated costs [4]. Nevertheless, these characteristics offer significant opportunities for implementing renewable technologies such as solar photovoltaic and wind energy [1], [5].

Studies in different parts of the world have shown that the decreasing costs of renewable technologies and advances in their efficiency have made them competitive with conventional energy sources, especially in isolated areas [5]. These technologies can be crucial in electrifying remote communities in mountainous areas, contributing to the region's socioeconomic development, and improving their inhabitants' quality of life [1]. However, assessing the feasibility and efficiency of these technologies in such environments requires a thorough analysis of the available natural resources and specific environmental conditions.

The article presents a detailed bibliometric analysis of renewable energy generation technologies applicable in high mountain areas. A systematic review of the scientific literature was carried out using the PRISMA methodology, and the data were analyzed using VOSviewer software to identify the most prominent trends in renewable energy research in these ecosystems. The study focuses on solar and wind technologies, analyzing the factors influencing their performance, such as solar radiation variability and wind patterns, and critical technical parameters, such as minimum wind speed according to the Weibull distribution [6].

Therefore, the main contribution of this study is a clear overview of the most documented and viable technologies for power generation in mountainous areas, to support the development of sustainable energy projects adapted to these environments. Through a systematic review and a bibliometric analysis, this research highlights the most relevant renewable energy technologies and their applicability in high mountain ecosystems.

The paper is organized as follows: Section II presents the Methods and addresses the theoretical framework, focusing on Non-Conventional Renewable Energy Sources (NCRE) and the characteristics of high mountain ecosystems. It also outlines the methodology applied, which includes the PRISMA systematic review and the bibliometric analysis using VOSviewer software. Section III combines the results and discussion, providing a detailed analysis of these results, highlighting the most viable generation technologies in moorland ecosystems, a type of neotropical alpine tundra ecosystem that plays a crucial role in water regulation and biodiversity. This section also interprets the results within the context of NCRE and the environmental characteristics of moorlands. Finally, section IV concludes with the main contributions of the study and recommendations for future research in this field.

2. Methods

2.1. Theoretical framework

Users located in high mountain areas require unconventional energy management due to their geographic dispersion and exposure to adverse climatic conditions [7]. These ecosystems, in addition to their richness in flora and fauna, play an essential role in the collection and regulation of fresh water, vital characteristics for maintaining the water balance of regions at lower altitudes above sea level and guaranteeing the availability of this resource in neighboring areas. Given that moorlands and other mountainous regions are often primary sources of water for thousands of communities, any intervention aimed at generating energy in these ecosystems must consider the impacts on their capacity to store and distribute water, since the alteration of these natural processes could generate adverse effects on the sustainability of local and regional water resources [8]. Therefore, human intervention in these ecosystems for power generation should not disrupt the normal development of these ecosystems [9]. Eligible sources for power generation in these areas should be considered according to the energy potential and the level of ecosystem intervention. Climate change is expected to affect hydroelectric generation in the coming years. For this reason, it is advisable to join efforts to diversify the sources of electricity generation, expanding the application of alternative technologies [10].

Detailed studies on wind potential in high mountain ecosystems are currently limited. However, the highest wind farm in the world is located in Ecuador at 2720 meters above sea level. Its strategic location on the peaks of some mountains in the province of Loja in the Andes Mountain range takes advantage of the excellent wind potential of the site by reducing the incidence of orography on wind speed [1]. Therefore, the possibility of locating wind turbines in high-altitude mountainous areas can be considered.

Furthermore, there are few studies on solar photovoltaic generation in mountainous terrain to determine its viability. The study by Karpic, Jelenco, and collaborators, however, shows that these generation systems have a more stable performance in high mountainous areas than sites at lower altitudes above sea level [11].

In this context, alternative energy sources are obtained from natural resources that are considered inexhaustible or continuously regenerated. These energies represent a sustainable and clean solution compared to fossil fuels, since their generation does not produce significant greenhouse gas emissions and therefore does not directly contribute to climate change [12]. The use of Non-Conventional Renewable Energy sources (NCRE) is of great importance for protecting high mountain ecosystems, which are especially vulnerable to environmental changes. At the same time, these regions offer enormous potential for the development of renewable energies, such as solar and wind power, which can be sustainably harnessed to generate electricity without compromising biodiversity or the natural balance of these environments [6], [12].

The following are some of the leading renewable energy sources with the potential for generating electricity in these environments, considering the particular geographic and climatic conditions of mountainous areas:

- Solar Energy: Solar Energy is manifested on the Earth's surface through radiation. It is harnessed to generate electricity mainly through the use of photovoltaic panels. These elements are composed of semiconductor cells that directly convert sunlight into electricity through the photoelectric effect. The energy generated is used to power electrical systems in various applications, from homes and buildings to industrial facilities, providing a clean, renewable energy source that reduces dependence on fossil fuels and contributes to climate change mitigation [12].
- Wind Energy: Wind Energy is obtained from the electromechanical conversion process carried out by wind turbines, which are made up of large blades connected to an axis on which the electric generator is installed. When the wind circulates, the blades rotate and transfer the wind's kinetic energy to the shaft, turning a generator that produces electricity. The electricity generated can be used to supply homes, businesses, and industries as well as to feed the electrical grid [13].
- Hydroelectric Power: Hydroelectric power is obtained based on the movement of water, either in rivers, natural streams, waterfalls, or through the use of artificial reservoirs. Hydropower generation is obtained in hydroelectric power plants that harness the kinetic energy of water to produce electricity. The process generally involves diverting water flow to turbines coupled to electric generators [14].
- Biomass Energy: Biomass energy is obtained from organic materials such as plants, agriculture, forestry, urban residues, organic waste, and animal manure. The conversion of biomass can produce heat, electricity, or biofuels. While the traditional application was limited to direct combustion for heating and cooking, modern technologies allow for a more efficient use of the raw material [15].
- Geothermal Energy: Geothermal energy comes from the natural heat in the earth's interior. This energy source uses the temperature difference between the hot core and the Earth's crust. In geothermal power generation, wells are drilled in areas with high underground temperatures to harness the heat to generate steam to drive turbines coupled to electricity generators [16]. On the other hand, geothermal heating

and cooling systems use the ground's thermal stability via subsurface heat exchangers to warm buildings in winter and cool them in summer. Geothermal energy has advantages such as constant availability without dependence on climatic conditions and low greenhouse gas emissions. However, its application is limited to specific geographic regions and requires a significant initial investment [16].

Additionally, high mountain ecosystems are natural biomes located in the upper altitudinal zones of mountain ranges, characterized by extreme environmental conditions, such as low temperatures, high ultraviolet radiation, and poorly developed soils. These areas are generally located above the altitudinal limit of arboreal vegetation, known as the tree line. These extreme environments present particular climatic and geographic conditions that have given rise to unique adaptations in the flora and fauna that inhabit them [17].

These ecosystems play a crucial role in climate regulation, biodiversity preservation, and the provision of water resources. The distinctive characteristics of high mountain ecosystems are reflected in a highly adapted flora [18]. Plants in these environments are often shrubs resistant to low temperatures, intense winds, and poor soils, thriving in rocky substrates and adverse conditions.

Generally located at altitudes above 3,000 meters, high mountain ecosystems face decreased oxygen availability and lower temperatures. Adverse climatic conditions, such as low temperatures and strong winds, limit biological activity and favor the growth of species adapted to these harsh conditions. Despite the adversities, these ecosystems harbor many endemic species [18].

In addition to their ecological value, high mountain ecosystems offer opportunities for renewable energy generation, such as photovoltaic and wind energy. The integration of these technologies in such environments can contribute to sustainable electricity production, taking advantage of the characteristics of these ecosystems without compromising their ecological integrity [17],[18].

2.2. Materials and methods

This study employed a systematic literature review methodology, prioritizing the most cited and relevant publications in the leading scientific databases. This approach facilitated a bibliometric analysis to evaluate the state of the art of electric power generation in high mountain environments, addressing the technical and environmental factors required to operate in extreme climatic and topographic conditions. The study begins by characterizing the selected publications through their annual distribution, document types, research areas, and most cited works. Subsequently, a bibliometric analysis was applied to examine the most influential countries/regions, institutions, prominent authors, and their collaboration networks, allowing the identification of trends, patterns of scientific cooperation, and the relative impact of key players in the field of study.

Following this methodological framework, the bibliometric method is a quantitative technique used to analyze scientific literature and measure different aspects of research activity. This approach makes it possible to evaluate scientific production, identify trends and patterns, and measure the impact of publications and researchers. It is presented as a powerful tool to understand and evaluate the dynamics of academic production, providing a quantitative basis for decision-making in research on energy generation technologies in high mountain areas [19]. The fundamental characteristics of the bibliometric method are measured through various recognized indicators, such as the number of publications, total citations, and average number of citations per publication. In this context, the analysis mainly covers the following aspects: citation analysis, co-authorship, burst detection, co-occurrence, and temporal analysis. VOSviewer bibliometric analysis software was used in this study, which offers advanced visualization capabilities to identify emerging trends and transient patterns in the literature on electric power generation technologies in high mountain ecosystems.

To maintain methodological rigor, this study adhered to a systematic literature review protocol. The process began with an exhaustive search of the relevant literature in bibliographic databases such as Scopus. Following this, predefined inclusion and exclusion criteria were applied to filter the results and identify the studies most aligned with the research question. From the selected publications, key data (including study design) were systematically extracted. Finally, the quality of each study was evaluated using standardized tools appropriate for its specific type [5]. A critical phase of this methodology involves the systematic analysis and, where applicable, meta-analysis of the extracted data [20]. This process employs statistical techniques to aggregate findings from individual studies, generating overall effect estimates. These synthesized results are then interpreted in the context of the initial research question while accounting for the limitations of included studies.

For data collection, information on electric power generation technologies in high mountain areas was obtained from the academic databases Scopus and Web of Science. To ensure a precise and comprehensive search, the process began by analyzing the specialized terminology used in these databases. A thesaurus was employed to organize and select the most effective keywords, which included the following specific terms to improve the precision of the bibliographic search:

- Mountain ecosystem, high mountain areas, and mountain environment.
- Renewable energy, energy generation, renewable energy generation.

Regarding data selection, the source choice was guided by criteria including publication year, author consistency, document type, and specific research areas. Additional inclusion and exclusion criteria -including document type limitations and the use of selected thesaurus keywords- were implemented to guarantee the relevance of the studies for the subsequent research development.

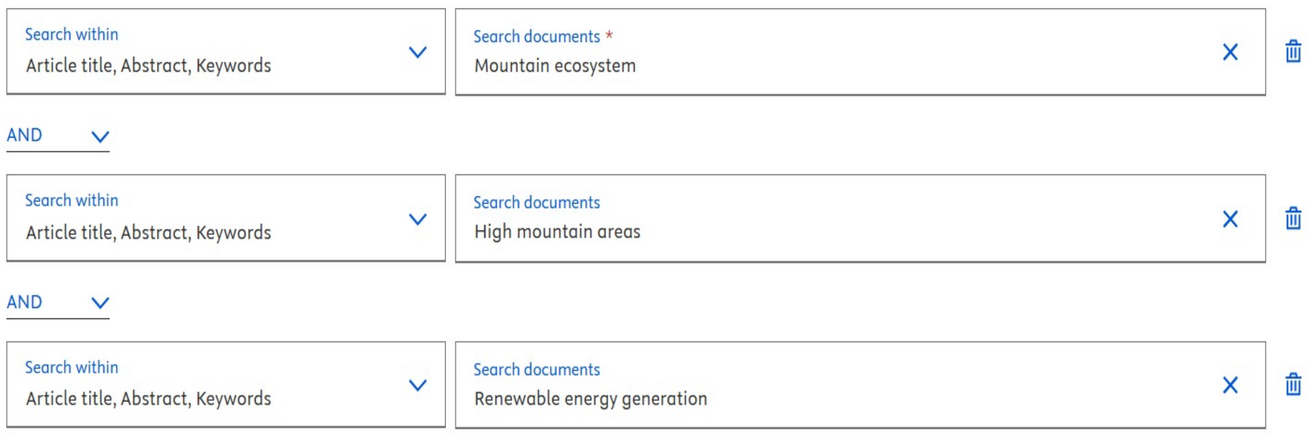

Figure 1. Scopus search engine. Data selection was based on the results obtained from the academic databases Scopus and Web of Science. For this search, the technical words identified in the thesaurus were used, as previously described and as shown in Figure 1.

The initial search yielded 1,868 relevant documents in Scopus and 3,407 in Web of Science. After applying consistent filters -including search fields, publication year, and document type- the results were refined to 156 and 811 documents, respectively. Subsequently, the information extraction process was carried out by searching and selecting documents within the chosen databases, applying selection criteria based on characteristics such as article title, authors, year of publication, journal or conference, number of citations, and other relevant variables. Subsequently, the collected data was exported in RIS or CSV format and consolidated into a RIS file using a text editor. This unified file served as the directed input for generating the bibliometric map through VOSviewer software.

VOSviewer is a software tool designed to analyze and visualize scientific information such as co-citations, co-authorships, and keyword co-occurrences in databases such as Scopus and Web of Science [19],[20]. This software identifies connections and relationships between different elements in scientific research. Once the data has been collected, filtering and preparing it properly for analysis in VOSviewer is essential. This process includes eliminating duplicate data, standardizing author and institution names, and defining a specific study period to enable a more precise analysis. These steps ensure the quality and accuracy of the results obtained [20].

After data preparation, he processed information was imported into VOSviewer, which supports different file formats such as CSV files, co-citation networks (e.g., Pajek), and term-per-document matrices (such as TF-IDF). After import, bibliometric analysis is performed using techniques such as co-citation analysis, co-authorship analysis, and co-keyword analysis, which allow the discovery of interrelationships and clustering in scientific data. Once the analysis is complete, VOSviewer generates visualizations, including network maps, density plots, and bar charts. These visualizations represent the structures and patterns in the dataset, facilitating an understanding of the relationships between the actors and issues studied.

Finally, the results obtained in VOSviewer are interpreted to identify the most relevant authors, topics, and trends over time. This process provided valuable information about the current state of research on power generation technologies in high mountain areas, which may be important for future research in this field.

3. Results and discussions

This section details the research findings, beginning with an overview of the publications landscape and proceeding to specific analyses of collaboration networks. Furthermore, it continues with the discussion of the implications of these results for renewable energy generation in high-mountain ecosystems.

3.1. Bibliometric map

A total of 156 bibliographic references were considered for the interpretation of the bibliometric map generated in VOSviewer. The analysis of the most relevant documents requires an understanding of the key elements present in the map and their interrelations

Each node in the map represents a scientific article, author, institution, or other entity, depending on the data used to create it. The nodes are connected by lines that represent relationships between them, such as co-citation, co-authorship, or co-occurrence of keywords. Also, their colors correspond to specific groupings in the bibliometric feature space, where groups of nodes of the same color tend to have similar characteristics or be related to topics, authors, or institutions.

In addition, node size can indicate different bibliometric metrics, such as the number of citations received, the number of publications, or relative influence in the field. Larger nodes usually represent more important or influential elements. The spatial distribution of these nodes can provide information about the structure of the research field; nodes closer together are usually more closely related in terms of content, while nodes farther apart may represent different topics or areas of research.

Analyzing these spatial and relational patterns reveals clusters that are groups of nodes that are densely interconnected with each other. Each cluster represents a subfield within the study area and its relationships and thematic proximity among the elements represented. The use of multi-year data enabled tracking the structural evolution of the bibliometric map over time, revealing emerging trends, declining research areas, and shifts in collaboration patterns among authors and institutions. Applying the methodologies and tools outlined for the bibliometric analysis of electric power generation in high-mountain areas yielded the bibliometric map presented in Figure 2.

According to the size of the nodes, the most relevant keyword in the topic of electric power generation in high mountain ecosystems is wind power. A cluster is formed around this keyword that groups terms such as electric utilities, wind turbines, wind speed, wind farm, renewable energies, and mountain regions. The keyword landforms are next in order of importance, and they are grouped with wind tunnels and topography to form another cluster. The term climate change follows in order of relevance, which is combined with the keywords' renewable energy resources, wind energy, and energy utilization to form a third cluster. On the left side of the bibliometric map, there is a high concentration of the three most essential clusters; among them, a strong interaction denotes the co-occurrence of keywords in the analyzed publications.

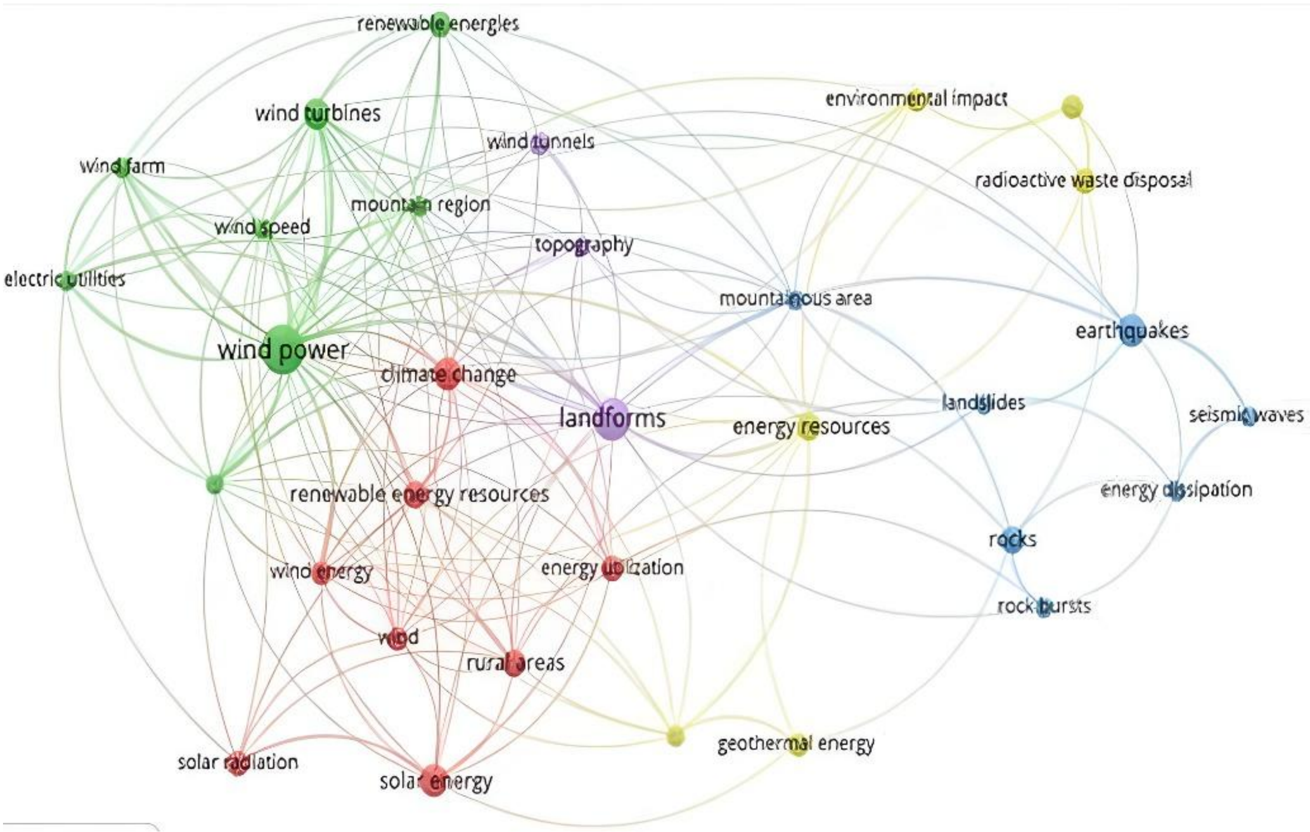

Figure 2. Bibliometric map of the relationship of keywords in electric power generation in high mountain ecosystems

3.2. Analysis of results

The bibliometric map provided by VOSviewer identifies wind power generation technology as the most researched, with a predominance of studies focusing on its application in high mountain areas. This conclusion is supported by several factors related to the physical and environmental characteristics of these regions. High mountain areas experience low air density but high wind speeds, maintaining the necessary momentum for a turbine to move; this, coupled with the topography and lack of obstacles interrupting the wind flow, creates ideal conditions for wind power generation [1].

Additionally, the topography of high mountain areas offers locations that allow capturing winds at higher altitudes, where wind speed is usually higher with respect to lower altitudes [21]. At these higher altitudes, the decrease in air density presents a dual effect on wind power generation. While it directly reduces the power output of the turbine for a given wind speed, it is concurrently associated with higher wind speeds, which can partially compensate for the loss of air density [22],[23].

Wind power generation also produces lower greenhouse gas emissions than conventional energy sources such as fossil fuels, making wind energy environmentally friendly and sustainable, particularly in sensitive environments such as mountains [24]. Compared to installing wind turbines, the construction of micro hydropower plants in high mountain areas usually has a greater environmental and economic impact due to the diversion of water courses, which can alter local ecosystems and affect economic activities such as fishing [25]. In contrast, wind turbines do not require significant modifications to water resources or topography, making them a more environmentally friendly option.

Another advantage is that wind power generation does not require water resources for its operation, making it a very beneficial option, particularly in areas where water resources are scarce. This independence from available water in high mountain regions makes wind energy a sustainable solution, as it does not compromise the water supply for other activities, such as agriculture or human consumption [26].

Wind power generation ensures energy supply through proper planning and integration into a diversified matrix of energy sources. Its incorporation into a diverse energy system is key to maintaining a constant flow of electricity. However, due to its intermittent nature, wind energy does not respond immediately to variations in demand, requiring the support of other sources or storage systems to ensure supply stability [27]. The integration of wind power remains highly valuable, as its use reduces dependence on fossil fuels, enhances energy security, and decreases vulnerability to fluctuations in the price of these resources [28].

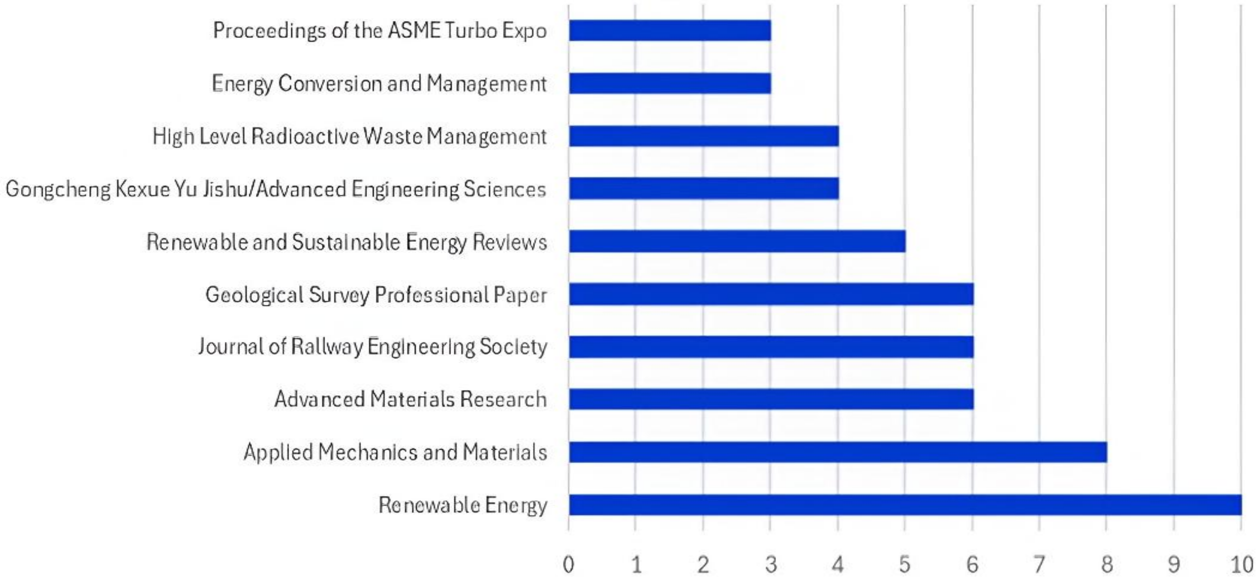

Figure 3. Leading journals included in the bibliometric analysis

The results of the bibliometric map on electric power generation in high mountain areas reveal three significant areas of study: wind energy, topography, and climate change. The viability of these systems is closely linked to climatic conditions [29], the geographical characteristics of the terrain, and the impact of environmental variations on energy production. Studies based on meteorological data and simulation models have made it possible to evaluate the performance of renewable energy in these environments, considering the challenges posed by the irregularity of the relief and the influence of climate change on the availability of energy resources.

Figure 3 presents the ten journals included in the bibliometric study, highlighting those that have published the most significant number of papers on the topic of power generation in high mountain areas. This information identifies the most relevant sources within the investigated field, providing an overview of the main means of disseminating knowledge on this topic. The documents are classified according to the year of publication or creation, using text processing techniques to extract the relevant information from each one. This analysis is based on data provided by the Scopus database, and the results obtained are summarized in Table 1.

The annual distribution of publications on renewable energies, shown in Figure 4, reveals that this field has been actively researched for decades. The data shows an upward trend in publications between 2002 and 2007, which was followed by a decline until 2012. A resurgence in research output, however, is evident from 2017 onwards.

Table 1. Number of citations per document

Title	Authors	Quotations
Multicriteria GIS modeling of wind and solar farms in Colorado	[30]	8.6
Renewable energies and ecosystem service impacts	[31]	107
The development program of hot, dry rock geothermal energy in China	[32]	100
Output Analysis of Stand-alone PV Systems: Modeling and experimental validation	[33]	44

Title	Authors	Quotations
The progress of fuel cells for Malaysian residential applications	[34]	36
Inclined solar chimney for power production	[35]	36
Assessment and statistics of Brazilian hydroelectric plants	[36]	36
Utilization of Meteorological satellite-derived radiation data	[37]	31
Urban-rural solar radiation and atmospheric turbidity	[38]	30
Sand erosion technique applied to wind resource assessment	[39]	20

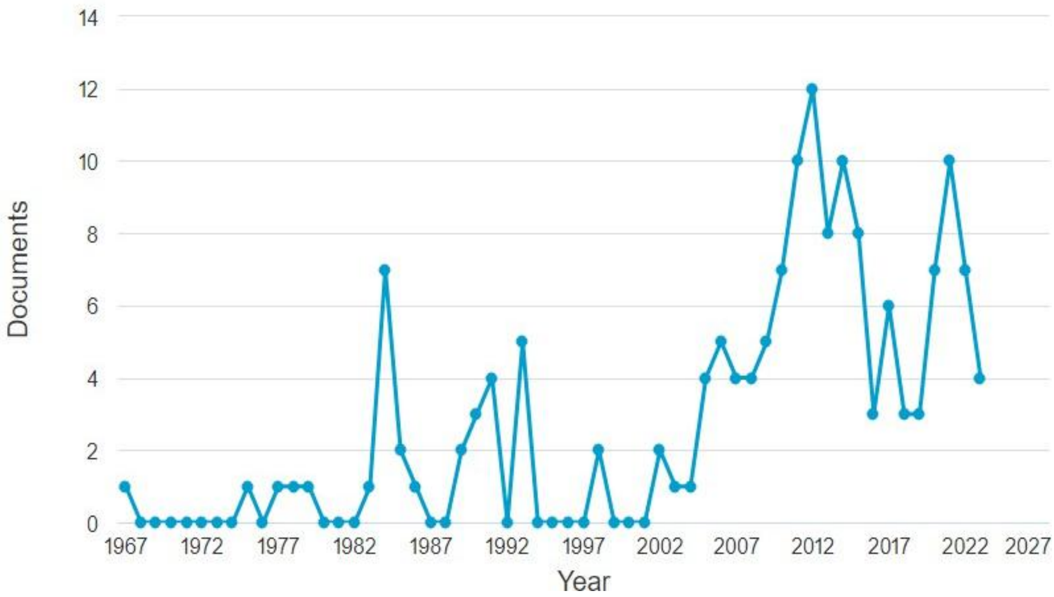

Figure 4. Document analysis

Renewable energies have maintained a consistent research interest over time. As Figure 5 shows, publication volume on this topic has increased over the past twelve years.

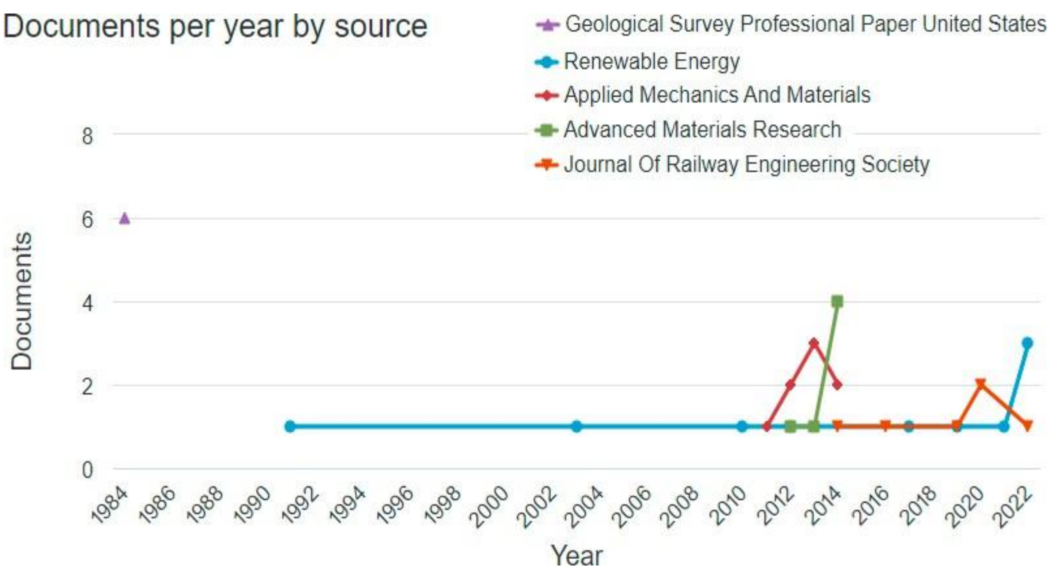

Figure 5. Analysis of documents by resource

The analysis of the number of documents published per author facilitates the search for information by allowing the identification of coherence, patterns, and trends among publications. As shown in Figure 6, this analysis is essential in constructing the bibliometric map.

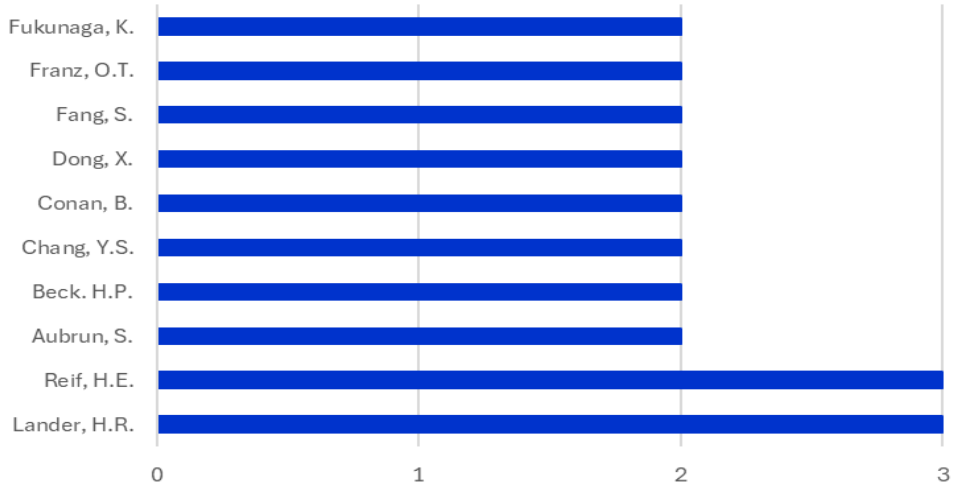

Figure 6. Analysis of documents by the author

Analyzing the number of documents published by universities and research entities identifies coherences, patterns, and trends among institutions, thus facilitating the search for information. As illustrated in Figure 7, this type of analysis is important in understanding the contribution and impact of each entity in the field of study. The analysis by country, presented in Figure 8, reveals that China has the most significant number of studies on renewable energy generation in high mountain areas, followed by the United States.

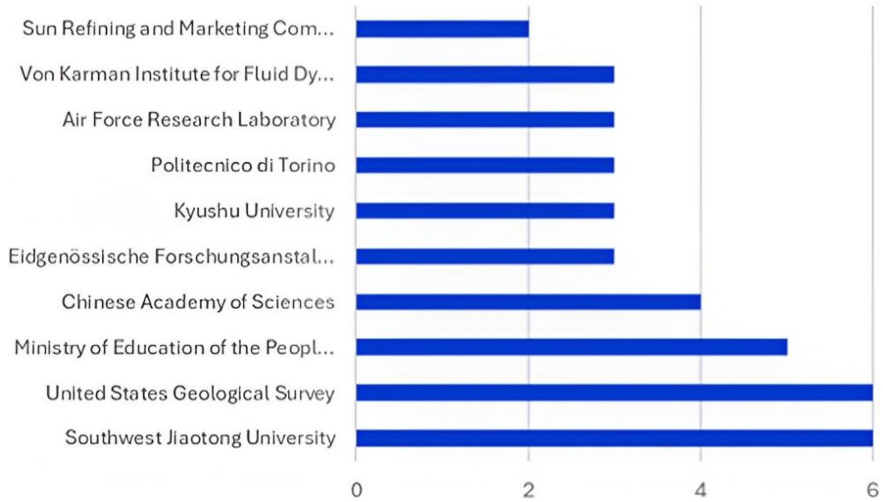

Figure 7. Analysis of documents by the university and the research entity

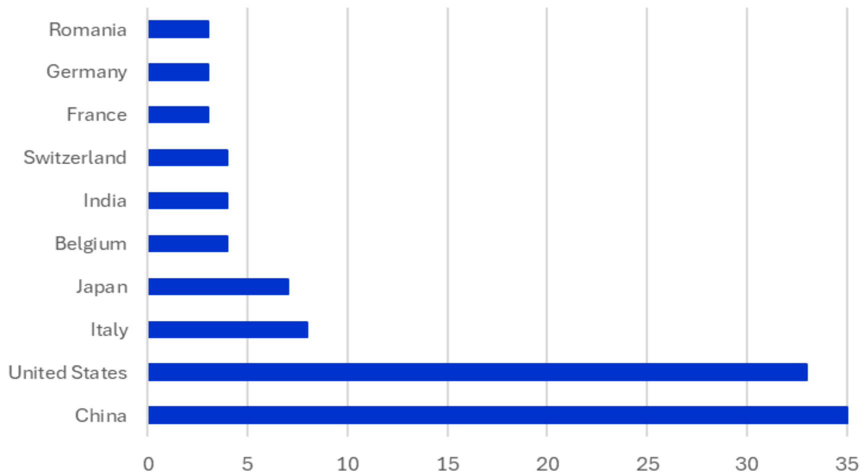

Figure 8. Analysis of documents by country

As illustrated in Figure 9, articles are the predominant document type in this research, constituting 47% of the total. These articles provide a detailed analysis of the results obtained from the Scopus database in line with the established search criteria and the research objectives.

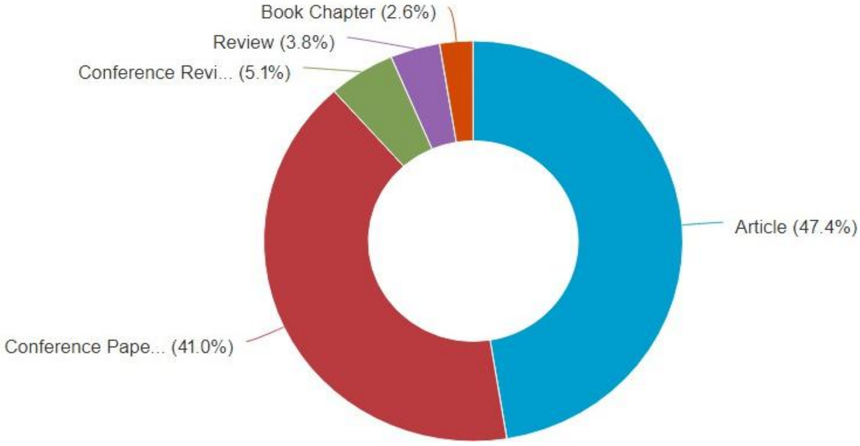

Figure 9. Analysis by type of document

3.3. Discussion

The availability of natural resources, such as water, sunlight, and wind, is a key factor in the design of energy systems for high mountain areas. These territories have a great variability in the number of available resources, which requires on-site reviews to determine the types of resources that can be harnessed. For example, in regions with abundant water resources and steep slopes, micro-hydroelectric power may be a viable option, while in areas more exposed to the sun or wind, photovoltaic or wind technologies can play a key role.

Extreme climatic conditions and rugged topography present additional challenges for the installation and maintenance of energy infrastructure. These factors affect the technological choice and long-term viability of projects in mountainous environments near the Andean moorlands. Existing infrastructure, such as roads, power grids, and storage systems, strongly influences the implementation of new energy solutions. The absence of conventional grid connections may require the adoption of hybrid or stand-alone systems, which reinforces the need for flexible and adaptive solutions. Not only should the technical requirements of the projects be considered, moreover, the specific needs of the local community, including its consumption profile, its operation and maintenance capabilities, and its acceptance of the use of new technologies. A community-centered approach that integrates technical expertise with local participation favors the social and technical sustainability of energy supply.

Technologies for power generation in high mountain areas have made great progress in recent years, allowing greater adaptation to the adverse orographic conditions and the energy potential available in these territories. Solutions such as micro-hydroelectric power plants, solar panels, and wind turbines designed to operate at high altitudes are showing increasing levels of viability. The deployment of these technologies is not without ecological and social impacts that must be carefully assessed. Mountain areas are often home to fragile ecosystems and sensitive biodiversity; thus, technological intervention can generate negative effects on the biodiversity of an area if it is not carefully planned. In addition, the introduction of energy infrastructure can alter local social and economic dynamics, especially if the needs, values, and ways of life of the communities that inhabit these regions are not taken into account.

The active participation of local communities in all stages of the process, from the identification of needs to the operation and maintenance of the systems, is of great importance for the long-term sustainability of energy projects. Technological appropriation, strengthening local capacities, and respect for traditional knowledge are key factors in social acceptance and the generation of benefits from such technological initiatives. An integrative approach that combines technological innovation with social justice and environmental responsibility will make possible the development of sustainable energy solutions in high mountain environments.

The use of wind turbines in areas close to Andean moorlands can generate negative effects on the flow of humid winds, which are fundamental for the maintenance of fragile ecosystems. Moorlands play a crucial role in regulating the hydrological cycle by capturing and storing water, which is then slowly released into local water sources. The installation of wind turbines in these territories can alter wind dynamics, precipitation patterns, and affect the moorland's ability to capture moisture. The presence of large structures such as turbines induces turbulence in the air, which alters the natural flow of wind and decreases the availability of water in the surrounding areas. These impacts can have serious consequences for biodiversity and the communities that depend on the moorlands, which underscores the need for a thorough environmental impact assessment before the implementation of wind projects in these areas.

The installation of solar farms on land near moorlands would generate alterations in these fragile ecosystems. High mountain areas are important for water regulation and biodiversity conservation, and their balance is affected by changes in land use. The construction of solar installations implies the transformation of the terrain, which can alter the natural drainage patterns and the capacity of the moorlands to capture and store water. The occupation of large tracts of land for the installation of solar panels can reduce the habitats of native species and disrupt ecological connectivity in protected areas. There is a risk that the reflection of the panels will change the microclimatic conditions in nearby areas, which may influence local vegetation and fauna.

Future research in the field of renewable energy generation in high mountain areas should focus on the evaluation of the long-term environmental impacts that may be caused by the implementation of technologies such as wind turbines and solar farms. It is vital to develop methodologies that monitor the effects of these types of projects on wind dynamics, moisture uptake, and drainage patterns in the moorlands. The study of predictive models that integrate climatic, ecological, and socioeconomic variables could help to predict the potential effects of new installations, ensuring that the preservation of high mountain ecosystems is not compromised. Research should explore methods for integrating renewable energies, such as the use of low-impact technologies and the implementation of adaptive design solutions.

Another aspect of future research is the study of the effects of technological intervention on the biodiversity of the moorlands. Although these ecosystems are adaptive, disturbances caused by energy projects alter species and ecological interactions, greatly affecting the surrounding plant and animal communities. Studies are needed to analyze the impact of energy generation technologies on local flora and fauna. These studies could help in the design of mitigation strategies to ensure the conservation of biodiversity. Finally, research should address the role of local communities in the management and monitoring of energy projects in moorland areas. Community participation in the design and implementation of energy solutions is critical for ensuring that projects are acceptable and appropriate to local socioenvironmental contexts. Future research could explore collaborative governance models that include local people in decision-making to ensure that the benefits of renewable energy use are distributed equitably and that adverse social impacts are minimized. In addition, these studies could focus on empowering communities to actively participate in natural resource management to strengthen local resilience despite environmental and economic challenges.

4. Conclusions

The choice of technology for power generation in high mountain areas depends on several factors, including the availability of natural resources, climatic conditions, existing infrastructure, and the community's specific needs. A combination of several technologies will likely be necessary to ensure a reliable, sustainable power supply adapted to the conditions of the mountain environment.

Technologies for power generation in high mountain areas are evolving rapidly to take advantage of these areas' energy potential and meet the challenges presented by geographic and environmental conditions. However, it is important to carefully consider these technologies' social and ecological impacts and ensure local communities' participation in their development and implementation.

This paper presented a bibliometric analysis of relevant publications on power generation in high mountain areas from different perspectives, highlighting their essential characteristics, knowledge structures, hot spots, and development trends. The analysis of publications and citations shows a general upward trend. The publications are mainly articles (47.4%), followed by conference papers (41%), while the remaining percentage corresponds to other types of papers (11.6%).

Regarding power generation in high mountain areas, China is the most productive and influential country, with the most significant amount of research conducted on the subject.

Keyword analysis indicates that research hotspots in high mountain power generation technologies should focus on terms such as "Mountain ecosystem," "High Mountain areas," "Mountain environment," "Renewable energy," "Energy generation," and "Renewable energy generation."

Based on the results of all the analyses in the current study, trends, challenges for future research, and limitations of the study are discussed. Technologies related to artificial intelligence can effectively solve problems associated with integrating renewable energies with power systems.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Data availability statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Author contribution

The contribution to the paper is as follows: Author 1, Author 2 and Author 3: study conception and design; Author 2: data collection; Author 3, Author 4, Author 5 and Author 6: analysis and interpretation of results; Author 1, Author 2, Author 3 and Author 4: draft preparation; Author 1, Author 5: project administration; Author 1, Author 4 and Author 6: writing review and editing. All authors approved the final version of the manuscript.

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