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Bibliometric Analysis and Review of Low and Medium Enthalpy Geothermal Energy: Environmental, Economic, and Strategic Insights

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ABSTRACT

Geothermal energy, an efficacious and readily available resource, has emerged as a sustainable alternative poised to satisfy escalating global energy demands. This study undertakes a comprehensive analysis of low (heat below 100°C) and medium (heat between 100°C to 150°C) enthalpy geothermal energy through a bibliometric approach and a literature survey, with an emphasis on the environmental and economic aspects. The methodological procedure encompasses: (i) systematic information processing and configuration, (ii) bibliometric assessment of the evolution and domains of the investigated field, (iii) evaluation of environmental and economic contributions, and (iv) Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, facilitated by a Focus Group comprising experts from the energy sector. The research on low and medium enthalpy geothermal energy has been identified as an expanding field, with five primary areas of focus: sustainability, cascade systems, heat pumps, numerical modelling, and groundwater potential in geothermal systems. Italy, the United States, and Germany have been recognized as the leading contributors in terms of scientific production. Geothermal energy, from an environmental standpoint, aids the decarbonisation process, reducing reliance on fossil fuels and other renewable energy sources. Although initial investment costs are considerable, the financial recovery period is relatively short. The promotion of geothermal energy, alongside the active involvement of academia, corporations, and governments, bolsters energy and socio-economic development, thereby contributing to the achievement of the Sustainable Development Goals (SDG).

1. INTRODUCTION

The escalating global demand for electrical power, primarily driven by industrialization and urbanization, has underscored the burgeoning significance of renewable energy within the global energy sector [1]. Traditional energy resources, such as coal, oil, and natural gas, necessitate sufficient capacity to sustain a balance between their availability and energy demand, as emphasized by Rosales-Calderon and Arantes [2]. Moreover, existing energy consumption patterns could potentially exhaust these nonrenewable resources in the ensuing decades [3]. Compelling interest in alterations to our energy paradigm also stems from issues relating to climate change, global warming, and energy security [4, 5]. Consequently, the global community is increasingly tilting toward renewable energy, viewed as a reliable energy supply with diminished environmental impact. Evaluating natural resources, such as biodiversity [6, 7], along with mining and energy resources [8, 9], has emerged as a primary strategy in various countries to ensure their future availability.

Projections by the International Energy Agency (IEA) suggest that the contribution of renewable energy to the total global energy capacity will experience a 50% upsurge between 2019 and 2024 [10]. Renewable energies, including wind, solar, biomass, and geothermal energy, underpin this growth. However, the global energy system has thus far only marginally adopted geothermal energy [11]. This form of energy originates from subterranean heat generated by rock temperatures, which increase with depth [12, 13]. The relationship between temperature and depth, defined by the geothermal gradient, dictates the feasibility and utility of this resource-a higher geothermal gradient implies greater potential for exploitation [14]. Depending on these conditions, geothermal resources can be harnessed for diverse applications such as electricity generation, heating, cooling, drying, dehydration, food processing, and balneology [15].

From 1995 to 2019, the number of countries utilizing geothermal energy escalated from 28 to 88, with a 52% increase in geothermal usage reported between 2015 and 2019 [16]. This growing interest in geothermal energy can be attributed to its non-reliance on weather conditions, granting it a distinct advantage over other renewable energy sources. Despite geographical constraints, geothermal energy can deliver consistent energy with a higher heat capacity than other renewable sources. Its efficiency hinges on enthalpy criteria and atmospheric conditions [17]. Geothermal energy resources are categorized into convective or hydrothermal systems, conductive systems, and deep aquifers, providing high, medium, and low enthalpy resources based on temperature. Resources with high enthalpy surpass 150℃, while medium-enthalpy resources range between 100℃ and 150℃, and low-enthalpy resources are below 100℃ [18, 19].

High-enthalpy geothermal energy, which constitutes 60% of the global installed capacity, has yielded remarkable results from economic, environmental, and energy efficiency perspectives [20, 21]. Although medium-enthalpy resources have been underutilized due to the technological limitations of the 20th century, contemporary technologies such as the Organic Rankine Cycle (ORC), Kalina Cycle (KC), and direct applications, facilitate the exploitation of these resources through hybrid renewable energy systems, providing efficient and cost-effective energy [22]. In recent years, low-enthalpy processes, primarily used in cooling due to climate change impacts, have seen significant development [23].

Low and medium-enthalpy geothermal energy have diverse applications, including heating-cooling, electricity, and water supply. As a response to socioeconomic growth and global climate variation, there is a rising need for refrigeration in the industrial, commercial, and residential sectors, particularly in Africa, Asia and Europe [24]. Clean cooling/heating resources are internationally interested in transforming renewable energy within the industrial sector, as the Renewable Energy Policy Network for the 21st Century's (REN21) Renewables 2018 Global Status Report indicates. According to a study by Gong et al. [25], "the geothermal industry is experiencing positive outside attention to its development activities".

The cooling mechanism involves extracting geothermal heat from the subsoil to the cold refrigerant to evaporate it and convert it into low-pressure steam. The compressor receives this steam to increase the pressure and temperature and finally transports it to the condenser to convert the hot vapour into a liquid state of high pressure and temperature [26].

The vital role of geothermal energy necessitates a comprehensive literature review of the contributions of the scientific community and its applications in the public and industrial sectors [15, 27]. Bibliometric and literature reviews provide a profound and detailed insight into this field of study, utilizing systematic tools or techniques to extract bibliographic information from databases such as Scopus and Web of Science (WoS) [28, 29].

Numerous literature reviews on low and medium enthalpy geothermal energy have been conducted globally, discussing topics like geothermal resource storage [30, 31], low-enthalpy geothermal exploitation mine-oriented enthalpy [32], the current understanding of the use of low-enthalpy geothermal energy cells for enhancing the energy efficiency of buildings [33], and the legal framework of superficial geothermal energy [34]. However, a comprehensive assessment of the economic and environmental aspects considered in this field remains elusive.

The relationship between the importance of geothermal energy and the literature review allows the generation of research questions such as: What research areas exist in the scientific production of low and medium enthalpy geothermal energy? What scientific contributions exist within geothermal energy's environmental and economic aspects with low and medium enthalpy?

This work aims to analyze the importance of low and medium enthalpy geothermal energy, through bibliometric analysis and review of existing literature published in Scopus and WoS, for a strategic vision of strengthening and importance of renewable systems and an analysis of its application's environmental and economic aspects.

2. MATERIALS AND METHODS

The methodology consisted of three stages: i) configuration and systematic processing of the information obtained from the Scopus and WoS databases; ii) generation of bibliometric analysis of production, contribution by country, and scientific distribution; iii) a literature review of the field analysed considering the environmental, technical, and economic aspects; and iv) analysis of Strengths, Weaknesses, Opportunities and Threats (SWOT) for the proposal of promotion strategies and strengthening of the field (Figure 1).

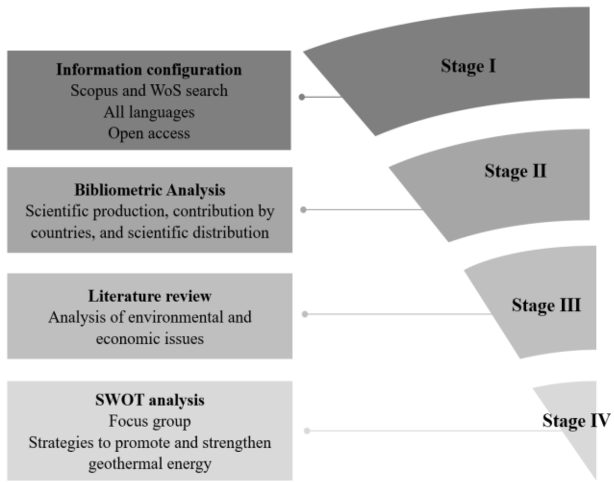

Figure 1. Methodological scheme of the study

2.1 Stage I: Information configuration

The study considered the Scopus and Web of Science (WoS) databases to obtain publication records. These databases were selected because of the many high-quality standard journals that index publications from various scientific disciplines, which is crucial for longitudinal and review analyses [35, 36]. This information contemplates studies conducted by academics and industrial entities focusing on energy development through Boolean term operators.

In the search, it was defined that the algorithm reflects information based on the titles, abstracts and author keywords. The search equation used the following topics and conditions: ("geothermal" or "geothermal energy" or "geothermal power")

AND ("renewable energy" or "alternative energy" or "green energy") AND ("low enthalpy" or "medium enthalpy").

Once the search was completed, the data were downloaded in Comma-Separated Values (CSV) and Bibtex formats. These records allowed bibliographic processing and generation of graphs to visualise the field's behaviour in phase two.

2.2 Stage II: Bibliometric analyses

The bibliometric processing carried out in this study contemplated three types of analysis: i) scientific production of the field investigated over time, ii) analysis of the contribution of studies by country, and iii) scientific distribution through an analysis of keywords that allow determining the research areas within the investigated field for the identification of the cognitive structure and intellectual relationships through the Bibliometrix software (version 4.0) [37] for the unification of databases and processing of the analyzed fields (e.g., citations, authors, countries, keywords) and VOSviewer [38, 39] for the bibliometric maps visualisation.

2.3 Stage III: Literature review

The literature review process contemplated research with environmental and economic considerations; for this, the full content of the publications were read and analysed, identifying the documents that answered the research question. According to the applied process, the analysed database was reduced to 13 scientific publications and fully reviewed. This phase allowed us to understand the environmental and political considerations within low and medium enthalpy geothermal energy.

2.4 Stage IV: SWOT analysis

The final stage of the work involved a SWOT analysis [40, 41] in determining strategies for promoting and strengthening research aimed at implementing low and medium-enthalpy geothermal energy, as well as its main benefits and limitations. The tool used for the analysis consisted of a focus group [42] composed of experts from the energy sector and experts from this study, considering unanimous opinions.

The experts included six members with academic and professional experience in energy resources, territorial planning, and sustainable management of natural resources. The analysis was conducted using a questionnaire divided into four axes: i) geothermal energy and the environment, ii) geothermal energy and technological development, iii) geothermal energy and legal framework, and iv) geothermal energy and economic viability. The different axes analysed included a series of questions aimed at jointly defining the experts' opinions on the topic under investigation. The criteria used to guarantee that the opinions were unanimous consisted of two rounds of the questionnaire for analysis at the national and global levels.

3. RESULTS

3.1 Scientific contribution

Research related to medium and low enthalpy geothermal energy began in 1984, with the study by Ungemach [43] which reflects the need for adequate techniques for exploring and evaluating geothermal resources, as well as the barriers associated with low enthalpy energy sources.

The first two decades (23 years until 2006) of research in the field are scarce, representing only 7.21% of the total scientific production. However, between 2007 and 2023, 92.79% of the investigations had an exponential growth trend with R2 equal to 0.8455, in which 2023 represents a decrease in production since it is the year in the course (Figure 2).

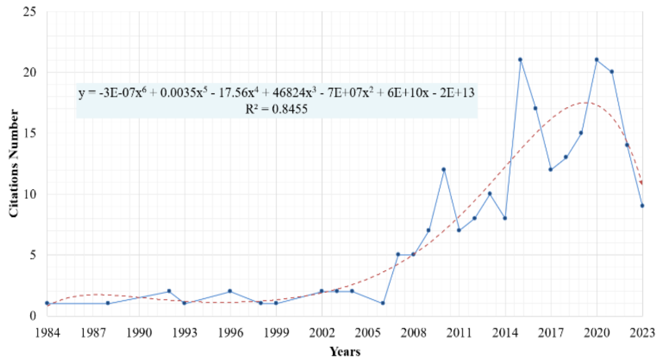

Figure 2. Behaviour over time of research related to low and medium enthalpy geothermal energy

The initial period (1984–2006) highlights research oriented toward planning and evaluating low-enthalpy geothermal energy projects [44] and their potential for electricity generation [45] and alternative uses [46, 47]. However, since 2007, over the last 26 years, scientific production has been increasing on issues related to the importance of geothermal energy in the transition towards sustainable district heating [48, 49], the design and evaluation of low-enthalpy geothermal systems [50-52], and assessments of the positive and negative aspects of geothermal energy from an environmental point of view [53-55].

3.2 Contribution by countries

According to the bibliographic coupling of countries with at least one medium and low enthalpy geothermal energy study, 42 countries contributed to research within the field (Figure 3). Generally, three countries stand out according to their scientific production: Italy (44 documents), Spain (22 documents), and Germany (17 documents). It is important to highlight Italy, Germany, and Greece as countries with the most cited studies globally (Table 1).

Table 1. Top 10 countries by the number of documents.

Ranking	Country	Region	Documents	Citations
1	Italy	Europe	44	847
2	Spain	Europe	22	191
3	Germany	Europe	17	528
4	Greece	Europe	14	229
5	United States	America	14	121
6	Mexico	America	12	150
7	China	Asia	9	56
8	Poland	Europe	9	82
9	France	Europe	8	33
10	United Kingdom	Europe	8	189

Figure 3 shows the bibliographic coupling analysis by country represented by nodes with variable sizes according to the number of documents registered. The links established in the graph reflect the existing collaboration between countries, in which thickness shows the strength of cooperation. Generally, bibliographic processing indicates 42 countries and 457 links with a relationship strength of 5684 grouped into seven clusters of different colours.

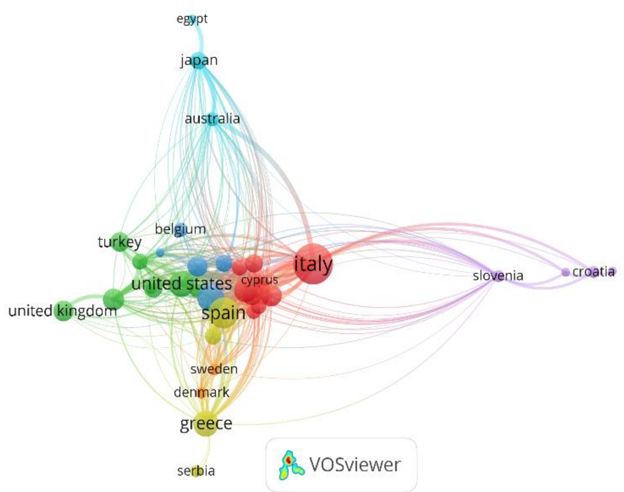

Figure 3. Country contribution bibliometric map.

Table 2 shows the country that produces the most by cluster and the top three countries it collaborates with. For example, the first cluster (red) contains 14 countries, of which Italy is the leader in production, and collaborates mainly with Australia, Germany, and the United States.

Table 2. Leading country in production by cluster and the top three countries with which it collaborates

Cluster	Country	Countries It Collaborates with	Link Strength
1	Italy	Australia	157
		Germany	132
		United States	96
2	United States	China	120
		Algeria	112
		Italy	96
3	Germany	Italy	132
		Norway	82
		Mexico	70
4	Spain	Austria	114
		France	83
		Italy	74
5	Croatia	Italy	40
		Slovenia	38
		Montenegro	38
6	Japan	Egypt	105
		Australia	60
		Iran	59
7	Sweden	Germany	57
		Denmark	47
		Italy	14

3.3 Research areas in low and medium enthalpy geothermal energy

According to the co-occurrence analysis of author words, connections and construction of a domain structure of 35 keywords were established. Table 3 shows the top 10 words with the highest frequency in the studied area, highlighting "low enthalpy", "heat pump", and "numerical simulation" as the three most frequent keywords.

Table 3. The 10 main words with the highest occurrence in low and medium enthalpy geothermal energy studies

Ranking	Keywords	Occurrences	Total Link Strength
1	low enthalpy	57	63
2	heat pump	19	22
3	numerical simulation	17	19
4	organic rankine cycle	14	12
5	geothermal heat pump	13	17
6	heat transfer	13	13
7	groundwater	10	21
8	borehole heat exchanger	8	14
9	district heating	6	5
10	enhanced geothermal system	6	6

The generated bibliometric map grouped the different keywords into five clusters, representing the research areas of low and medium enthalpy geothermal energy (Figure 4). The variation in the size of the nodes indicates the number of occurrences of the keywords, and the links reflect the relationships with other themes.

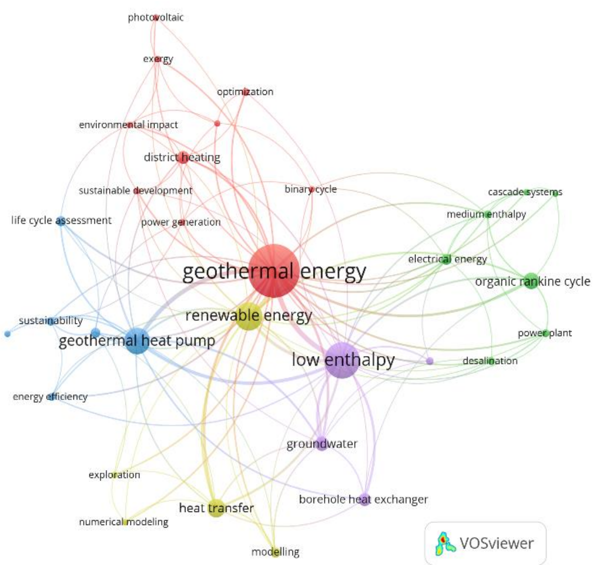

Figure 4. Author keyword co-occurrence bibliometric map in low and medium enthalpy geothermal energy

Cluster 1 (red), called *"Geothermal energy and its contribution to sustainable development"*, contemplates the understanding of the importance of low and medium enthalpy geothermal energy in global sustainable development and represents the most studied area within the field [56, 57]. Studies have analysed the role of geothermal heat sources in district heating and cooling to supply the global energy demand [48, 58] and evaluate its contribution as an environmentally friendly technique [53, 54].

The area called "cascade systems: geothermal polygeneration" includes cluster 2 (green) with research that promotes the use of geothermal resources at cascade levels, characterized by sequential use of subsoil heat for the combined production of electricity, heating or refrigeration, drying and dehydration processes, as well as recreational uses [15, 59]. This type of cascading energy use has been evaluated from technical and economic points of view, as well as it's potential as a rational and sustainable use of geothermal resources. On the other hand, there is evidence of studies on using Organic Rankine Cycle (ORC) technology for low enthalpy geothermal systems as profitable and efficient alternatives within this cluster [60, 61].

On the other hand, the area "geothermal heat pumps (GHP) as a tool for geothermal use" is identified, which includes cluster 3 (blue), in which the use of heat pumps is exposed as an alternative for the use of geothermal energy from low enthalpy, which allows the reduction of primary energy consumption and greenhouse gas emissions [62, 63]. Research in this area mainly contemplates the design and implementation of GHP as viable techniques from a technical and economic point of view [64, 65], considering the evaluation of impacts on the four damage criteria for each phase of the entire life cycle (production, installation, operation, and end of life) [66].

Likewise, it is possible to observe a trend of studies related to "numerical simulation for the design of geothermal systems" within cluster 4 (yellow) with research related to modelling or numerical simulation of geothermal systems under different physical-chemical conditions, existing lithology data, and soil temperature [67-69]. These studies evaluated different scenarios to identify the potential and limitations of geothermal systems [49, 70, 71].

Finally, cluster 5 (purple) contemplates the area called "groundwater in the use of geothermal energy", in which hydrogeological and thermal characterisation studies of shallow aquifers for use in heating and cooling systems stand out, as well as the evaluation of the environmental impact in the different stages of construction of this type of system [72-86].

3.4 Low and medium enthalpy geothermal energy: Environmental and economic overview

The review considered 13 studies that analysed the environmental or economic aspects of low and medium enthalpy geothermal systems (Table 4). The information analysis reflects that the contribution is focused on European countries, which evaluate the operation of low enthalpy geothermal systems for cooling or heating buildings, highlighting their environmental, social and economic importance. Additionally, studies have been conducted at a global and continental level to promote geothermal energy as a sustainable alternative.

Table 4. Scientific findings of economic and environmental aspects of medium and low enthalpy geothermal energy

Country	Reference	Study Aim	Study Findings
Italy	[52]	Design of a solar-geothermal system through a dynamic simulation model and an energy economic analysis	**Uses:** District heating-cooling and domestic hot water. **Economic aspect:** Savings of 31.4 GWh/year of primary energy (savings greater than 75%). **Environmental aspect:** Integration of geothermal, solar and biomass energy systems as sustainable alternatives to meet urban energy demand.
	[79]	Development of a thermofluidynamic numerical model for the design of an energy system that recovers the freezing probes installed in two tunnels	**Uses:** District heating-cooling. **Environmental aspect:** Opportunity to combine the heat extracted from the ground with heat pumps (improvement of efficiency and use of renewable energy sources). **Economic aspect:** The recovery of probes allows to cover the cost of drilling and installation of geothermal probes.
	[87]	Exergoeconomic and exergoenvironmental analysis of a binary geothermal plant with solar reinforcement	**Uses:** Electricity production. **Economic aspect:** System implementation cost of €6,513/kW, high compared to a conventional geothermal plant. The levelized cost of electricity from the new hybrid solar and geothermal plant is $0.15/kWh. **Environmental aspect:** Integration of geothermal and solar energy systems for the production of electricity.
	[80]	Evaluation of the feasibility of a low enthalpy geothermal heat pump (GSHP) for	**Uses:** Heating and cooling systems. **Economic aspect:** The implementation of the GSHP system allows reducing energy consumption, alleviating excessive expenses for the existing centralized system. **Environmental aspect:** From the environmental point of view, the study presents the GSHP system as green energy contributing to the industrial environmental commitment.
Serbia	[65]	Criteria analysis for the use of groundwater as a renewable energy source in geothermal heat pump systems	**Uses:** District heating/cooling. **Economic aspect:** They would reduce electricity consumption by 60% to 70% (150 kWh/m^2 would be saved per year, or €400-600 per year at nowadays' prices), with investments that would be recovered in approximately five years. **Environmental aspect:** Rich area from the geothermal point of view in its initial stage of installation of systems with the potential to reduce air pollution generated by other types of energy.

Global	[55]	Life cycle assessment of power generation in a geothermal heat pump system	**Uses:** Power generation, heating/cooling. **Environmental aspect:** Low levels of consumption of fossil resources and reduction of emissions into the environment.
European Union	[58]	Approach to local heat supply strategies for the countries of the European Union	**Uses:** Power generation, heating/cooling. **Environmental aspect:** Geothermal energy with potential for the partial or total decarbonization of European Union states. **Economic aspect:** Opportunity for geothermal energy with potential for the partial or total decarbonization of states of the European Union and satisfy 71% of the heat demand of buildings in areas.
United Kingdom	[88]	Design and evaluation of an open-loop geothermal heat pump in a mine water environment	**Uses:** Heating/cooling. **Economic aspect:** Operation and maintenance costs of the system with chemical water treatment are much lower than the mechanical cleaning of the filters (manual cleaning). **Environmental aspect:** Increase efficiency and reduce carbon emissions, and educate people on public participation to improve the future of geothermal system employment.
Canada	[82]	Assessment of the potential of geothermal energy to support local energy demand and its economic viability	**Uses:** District heating. **Economic aspect:** Thermal energy production >20,000 kWh per year with costs less than <10 c/kWh. **Environmental aspect:** Compatible energy to meet the heat demand by reducing primary electricity consumption.
Spain	[62]	Analysis of tourist infrastructures that make use of surface geothermal energy systems	**Uses:** Heating/cooling in tourist infrastructures. **Economic aspect:** Energy savings of 66% (374 MWh, €69,235) with investments that showed rates of return of more than 13%. **Environmental aspect:** Emission savings was 256 t CO_2 per installation and year.
Greece	[60, 86]	Economic and energy analysis between a heat pump system and other available technologies (natural gas, biomass and diesel)	**Uses:** Space heating, soil and greenhouse heating, agricultural drying, aquaculture, recreation. **Economic aspect:** High initial investment with fast recovery rates. **Environmental aspect:** Mitigate the emission of CO_2 into the atmosphere.
Chile	[78]	Design and implementation of a geothermal air conditioning system using a Ground Heat Pump (GHP) on an academic campus.	**Uses:** Heating/cooling. **Economic aspect:** Energy consumption savings (less 36% annual kWh). **Environmental aspect:** Efficient use of land as a renewable energy source on a university campus as a model of sustainable and replicable energy consumption.

3.4.1 Environmental aspect

Geothermal energy is a tool for solving the energy demand and reducing the environmental impacts of non-renewable energy sources. From an environmental point of view, low and medium enthalpy energy is a resource that reduces greenhouse gas emissions, which cause global warming [53, 76]. These techniques, commonly used in electricity generation, cooling, and heating systems, are widely used in urban and industrial areas with a clear objective of contributing to sustainable energy development.

The reviewed studies mainly reveal the functionality of low and medium enthalpy systems through case studies or global analyses, in which the use of geothermal energy is promoted internationally, complying with the current regulations of each country. According to Milenić et al. [65], shallow aquifers could be a strategic option for energy production for district heating and cooling as a medium or low enthalpy mechanism. These sources can increase the energy capacity of a city, reducing primary energy consumption by up to 60% and 70%, respectively. In Europe, various geothermal projects seek to supply the energy demand sustainably. However, efforts are still being made on other continents to promote this type of energy in urban systems, becoming a new technological challenge for adapting geothermal energy as a sustainable energy system [77, 78]. According to Carotenuto [79], it is possible to recover freezing probes connected to a thermo/cooling plant structured by a heat pump, inertial storage tanks, and circulation pumps. This system reduces the environmental impact and improves energy efficiency, adapting to the political guidelines of world organisations related to the change in the energy matrix and promoting the reuse of existing structures.

Although implementing geothermal systems represents a sustainable alternative, inadequate resource management can contribute to physical properties and soil temperature alterations [58, 80]. Among the environmental effects registered by geothermal energy, most consider the construction phase [81] owing to the diesel consumption by the drilling platform, the steel used for the casing of the wells, and the construction of the power plant [82, 83]. One option to mitigate these environmental effects is to use biodiesel or non-contact drilling technologies [84].

Another alternative for improving and optimising the efficiency of geothermal systems is the cascading use of low and medium enthalpy resources as a sequential technique of geothermal heat, generally for generating electricity, heating or cooling, recreational uses, or drying or dehydration processes [15, 85]. Finally, studies such as Lohse [53] recommend successful exploration to access geothermal deposits with minimal drilling efforts, thereby reducing the environmental impact in the construction stage.

3.4.2 Economic aspect

Economic evaluations show that geothermal systems are economically profitable in long- and short-term projects, but they will depend on the objective of the work (e.g., change in the matrix or energy expansion) [62, 82, 86]. A study by MacLean et al. [78] concluded that there were greater savings when cooling capacities were used instead of heating in geothermal mechanisms. Part of the economic investment is the heat pump and execution of the well for pumping and reinjection of the water used at the end of the industrial cycle.

Although the evaluation of the economic and environmental aspects of geothermal resources is rarely addressed in scientific literature, specific studies have presented the advantages and disadvantages of these aspects (e.g., [58, 62, 65, 83]). Implementing a geothermal system requires a novel concept of drilling that does not involve overpricing through an innovative design and intelligent measurement of business associations to reduce the initial investment costs significantly [77]. From an economic point of view, the transition of the energy matrix with a focus on geothermal resources represents a high investment in the construction stage. However, the recovery rate of this type of project is possible within a few years, depending on the magnitude of the implemented system [62, 86].

From the studies reviewed in this research, the authors pointed out three key points for achieving an efficient and profitable project: i) the participation of a group of companies that are interested or dedicated to geothermal exploitation works; ii) the technical use of studies carried out in this area to understand the case study and actual drilling costs; and iii) good communication in the exploration phase between geothermal companies and local communities.

3.5 SWOT analysis

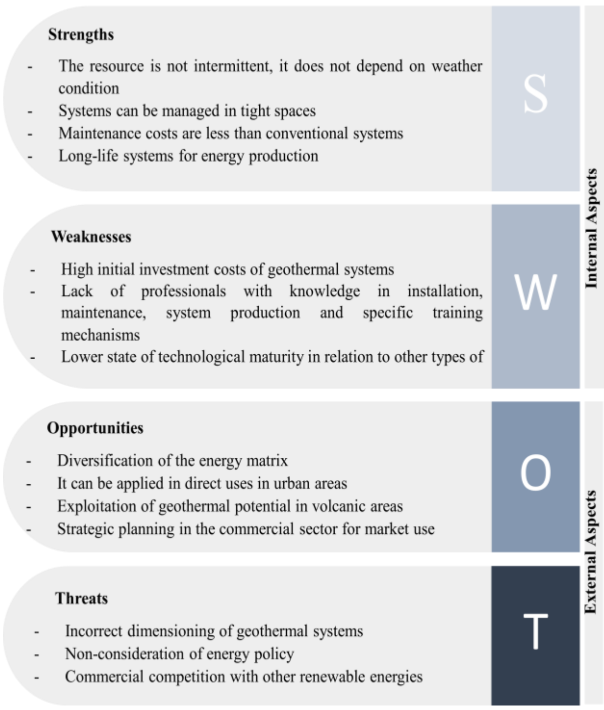

Figure 5. SWOT analysis of low and medium enthalpy geothermal systems

Figure 5 shows the SWOT analysis results focused on strengthening geothermal systems from economic, environmental, and political perspectives. SWOT analysis allowed us to identify the key factors, weaknesses, opportunities, and threats that can influence geothermal systems' potential and implementation rates.

In an internal context, reducing greenhouse gas emissions through surface exploitation systems with affordable maintenance costs is a strength of geothermal resources. This type of system is suitable for application in urban areas, reducing energy consumption and representing significant economic savings. However, among the weaknesses of this type of renewable energy, the high cost of the initial investment (construction phase) stands out, in which the drilling stage represents an environmental impact owing to the increased use of diesel.

On the other hand, from the analysis of external aspects, it is important to mention that geothermal systems represent an opportunity to diversify the global energy matrix, in which the increase of professionals with knowledge of exploration, exploitation, and maintenance in geothermal systems is essential. However, few political laws have supported this type of green energy. At the global level, politics, energy competition, and inadequate design of geothermal systems represent the main threats that condition resource exploitation.

Based on an analysis of the internal and external aspects of the investigated field, this study proposes strategies that promote the investigation of geothermal energy considering social, environmental, political, and academic aspects for the fulfilment of the Sustainable Development Goals (SDG). 7 (Affordable Clean Energy), 11 (Sustainable Cities and Communities), and 13 (Climate Action):

- Increase the promotion of geothermal energy in the industrial, commercial, and residential sectors to improve the acceptance and implementation of geothermal energy as a sustainable alternative.
- Contemplate polygeneration in cascade systems that guarantees sustainable and sequential use of the extracted resource.
- Within the government system, it is recommended to strengthen the political framework of renewable energies, promoting the financing of research that allows innovation in extraction methods and reduces investment costs. One of the reforms that could be included is a law to promote the extraction of shallow and deep geothermal energy with the respective technical, environmental, and social restrictions that guarantee success in decarbonising the environment and energy supply.
- Implement systems in tourist infrastructure to promote social awareness of the benefits of geothermal resources for humanity and the ecosystem. Some examples of geothermal energy tourism include balneology, educational trails, or greenhouses, in which tourists understand the potential of geothermal resources in tourism and their contribution to reducing environmental pollution.
- Design systems that combine renewable energy to improve efficiency in the extraction and use of geothermal energy.
- Contemplate the political and environmental aspects in the design of geothermal systems that guarantee sustainability in the short, medium, and long terms.

4. DISCUSSION

The methodological approach used in this study allowed the integration of three types of analysis within the field of low and medium enthalpy geothermal energy research: i) bibliometric analysis to evaluate scientific production and distribution, ii) literature review of economic aspects and environmental factors considered within the field, and iii) SWOT qualitative analysis to establish promotion strategies and strengthen geothermal resources.

According to the bibliometric analysis, the scientific production of low and medium enthalpy geothermal energy has developed since 1984, with exponential growth in the last 26 years, representing approximately 93% of the total output. This marked difference from the first two decades could refer mainly to the increase in scientific interest in promoting sustainable energy transition at a global level. Within this scientific boom in the field, it is possible to identify research focused on the design and evaluation of geothermal systems for urban and industrial use; integration of energy systems that combine sustainable sources; and analysis of technical, social, and environmental aspects that guarantee the functionality of the geothermal systems [52-54, 72]. On the other hand, it is important to highlight Italy, Spain, and Germany as countries with the greatest contribution to the field (Table 1). Italy's scientific contributions among these countries reflect the highest number of citations with collaborations with Australia, Germany, and the United States (Table 2).

Analysing intellectual structure through scientific maps based on keywords allowed us to define five research areas in low and medium enthalpy geothermal energy (Figure 4). Within these areas, it is important to highlight "cascade systems: geothermal polygeneration" as an emerging line of research within the field with a clear objective of sequentially using subsoil heat through polygeneration, combining different scales of use from electricity generation to recreational use [15, 59].

On the other hand, the review of scientific literature with contributions within the environmental and economic fields of geothermal energy exposes the importance of implementing this system to reduce greenhouse gas emissions that pollute the atmosphere and compromise ecosystems and human security [89, 90]. From an environmental perspective, the findings reveal that geothermal energy is a renewable energy source with minimal environmental impact, which mitigates air pollution generated by other types of energy. However, drilling in the construction stage is one of the main environmental effects of excessive diesel consumption. These problems can be mitigated by correctly selecting sustainable geothermal equipment, which will contribute to reducing these emissions and energy transitions in the face of environmental pollution problems [77]. According to Parisi and Basosi [91], developing technological equipment for deep geothermal exploitation will allow this energy to be a cleaner and safer source with greater social acceptability, considering that these technologies are intended for the reinjection of geothermal fluids. This progress will make it possible to strengthen decision-making in the planning and promotion processes of technologies, considering control in the manufacture of geothermal equipment [92, 93].

Considering the economic aspect, the literature review presents case studies that validate geothermal systems' economic viability compared with other energy types. The economic evaluations revealed electricity generation at costs below $0.15/kWh, representing primary electricity savings of up to 70%. Geothermal systems show viability in small- and large-scale projects with investments that can be recovered in the short term with rates of return greater than 10% [60, 62, 86]. The analysis of Ahmed et al. [89] indicates that geothermal systems have a low economic index relative to fossil systems, with a productivity of up to 17 years. Under technical conditions, geothermal heat pumps generate energy savings of 81 million tons for electricity generation from fuel-oil systems [16]. Under these statements, the findings of different investigations will depend on local conditions, the energy efficiency of the technologies in question, and the prices of subsidies.

Based on the focus group analysis implemented in this study, the proposed strategies strengthen the participation of geothermal energy in the industry, considering environmental, economic, technical, and social challenges. The analyses revealed that the need for effective mechanisms for implementation and commercial energy competition is the main barrier to promoting geothermal systems in urban sectors [94, 95]. Global experience indicates that government support is key to geothermal development through loan programs, industrial insurance, grants, and exploration projects [96]. In addition, Balzan-Alzate et al. [97] indicated that the acceptance and knowledge of this type of energy must be considered in the energy contexts of each country because the change in context could alter the objectives in the future.

Marketing strategies allow geothermal to compete with other types of renewable energy, through the contribution of government frameworks, for promotion at the urban and industrial levels [98]. Likewise, the scientific-academic contribution is important in training knowledge of installing, producing, and maintaining geothermal systems with application in urban or rural residences. This strategy reduces operational accidents and security risks to social communities.

Despite the low promotion and participation of geothermal energy in energy development, efforts by countries and world organisations that offer the benefits of geothermal energy have been rescued. In addition, some developing countries have shown an interest in developing industrial projects with geothermal systems [99]. For example, a dozen Latin American and Caribbean countries are working on developing power plants based on geothermal systems to reduce the use of fossil fuels and balance their economies [100, 101].

Within the tourism sector, the promotion of geothermal resources has high potential. Some studies have promoted balneology [102], the development of greenhouses [103], geothermal parks [104] and tourist trails [105] as strategies to promote community awareness through information panels on the potential and contribution towards sustainable development of geothermal energy globally [106].

Therefore, scientists have highlighted the importance of geothermal promotion to strengthen energy development in areas with resource scarcity problems [96]. This promotion can be achieved with multi-generic projects that allow optimal use, such as urban buildings that require electricity, heating, or cooling [107]. Under this premise, it is possible to affirm that any mechanism promoting the direct use of geothermal energy requires incorporating planning aspects related to territorial use.

This review highlights the importance of using medium- and low-enthalpy geothermal energy sequentially by implementing geothermal cascade systems. Additionally, it is recommended that future studies on medium and low geothermal research consider an analysis of the sociopolitical aspect as a conditioning factor for the success of this type of renewable energy.

5. CONCLUSIONS

The evolution of medium or low enthalpy geothermal energy corresponds to the development of renewable energy innovation originating mainly in European countries. This energy represents an alternative to industrial, political, and social interests and contributes to mitigating the effects of climate change. The bibliometric analysis and literature review carried out in this study reflects research that validates the sustainability of low and medium enthalpy geothermal systems compared to conventional systems through five research areas: i) geothermal energy and its contribution to developing sustainable, ii) cascade systems: geothermal polygeneration, iii) geothermal heat pumps (GHP) as a tool for geothermal use, iv) numerical simulation for the design of geothermal systems, and v) groundwater in the use of geothermal energy.

The literature review of the economic and environmental aspects of this type of system highlights energy savings, with a high investment recovery rate and minimal environmental impacts. However, the lack of public policy considerations that strengthen the implementation of geothermal systems as opportunities for social growth in urban or rural areas and industrial or energy production sectors is evident.

According to the SWOT analysis, geothermal energy, from the point of view of internal aspects, represents a sustainable energy source that mitigates environmental pollution and supplies global energy demand. However, the high investment costs and technological advances limit the applicability of this type of system. On the other hand, the analysis of external aspects mainly reflects the possibility of promoting geothermal energy through tourism, as well as the implementation of polygeneration systems that optimise the extracted resources; however, there is little support within the political framework in which it is necessary to guarantee sustainable exploration and exploitation from an economic and environmental point of view.

The strategies consider academic-scientific and political participation as a general link criterion between the various sectors, which can be managed in strategic areas with active geothermal systems for efficient production. This type of interaction would allow the implementation of efficient geothermal systems with considerable energy savings that can be replicated internationally to satisfy global energy demand.

Finally, the proposed methodological approach represents a tool for researchers to learn about the main research areas within low- and medium-enthalpy geothermal energy and to develop research on emerging topics. The main limitation of this study is the analysis of the academic literature. However, industrial and government sector information needs to be published and represents great value. Future research studies within the field should consider the environmental and economic analyses of different systems designed with political-social considerations that guarantee the acceptance and functionality of the system.

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