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Artificial Intelligence and Renewable Energy: Bibliometric Analysis

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***Abstract*—Taking into account that artificial intelligence (AI) is the computer technology that has seen the most explosive growth in recent years, we try to explore its application in the context of the concept of sustainable development, and our focus is on the possibilities of artificial intelligence to stimulate the development of renewable energy sources (RES). This is dictated by the interconnectedness and interdependence between the two areas of development – on the one hand, the need for "green energy" to power the artificial intelligence centres requires an increase in the production and consumption of energy from renewable sources, and on the other hand, an increase in the share of unconventional energy sources necessitates increasing storage capacity and efficiency in energy use, which relies on AI. With this study, we aim to identify the areas of application of artificial intelligence in the field of renewable energy (RE). Applying bibliometric analysis to the totality of publications subject to our research, we identify the leading authors and highlight their most significant developments, specify the sources with the highest concentration of publications and the countries from which they originate. By conducting a keyword co-occurrence analysis, we highlight the areas in which AI is used and the purposes for which it is applied. In conclusion, we formulate conclusions about the development of the leading technologies analysed. Finally, the results of the proposed research can be used as a basis for future research and as a useful indicator of the direction of technological developments at the intersection between artificial intelligence and renewable energy sources.**

Keywords— Artificial intelligence (AI), bibliometric analysis, renewable energy, renewable energy sources.

I. Introduction

The technological development of society in recent decades is a prerequisite for more innovative technologies to become a daily part of our lives. One of the clearest examples in this regard is AI, which has seen the most explosive growth in its development in recent years. Originally created as a machine to perform actions or perform tasks that require human intelligence [1] - [2], today, through the constant expansion of the boundaries of knowledge and capabilities for AI, it surpasses in the generally accepted case human intelligence and is capable of solving very complex and complex tasks in a short time, which predetermines its use in various sectors of human activity.

The relevance of our research stems precisely from the possibility of applying AI in directions where we identify deficits or developmentally critical barriers, such as the example of renewable energy. Although the idea of using RE is not something new, we have seen its strong development in recent decades, in the context of the concepts of sustainable development and the circular economy. The incentives provided by several governments to develop innovative renewable energy technologies, together with regulatory amendments to the legislation of several countries, have contributed to growth not only in production but also in the consumption of renewable sources, which inevitably led to several negative effects, including:

- Growth in the extraction of rare earth elements needed to produce renewable technologies.
- Increasing pollution in the production and use of renewable technologies.
- Expansion of the territories on which renewable energy sources are located, which has a negative effect on biodiversity.
- An increase in the volume of waste from end-of-life facilities and the need to create innovative technologies for the treatment and recycling of this waste.

We find these and other negative impacts of RE in the focus of researchers in recent years [3] - [6] and we believe that while studies in this research area are still insufficient to comprehensively uncover the impact of RES in the long term, they identify key areas where further studies and

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analyses need to be undertaken to address the existing negative effects.

It is here that we reveal the role of AI in supporting the activities of specialists and stakeholders – to increase the efficiency and quality of renewable energy and to limit and eliminate the already established negative effects caused by RES.

In this regard, we are trying to explore the application of RES in the context of the concept of sustainable development and the concept of circular economy, and in particular, our focus is on the possibilities of AI to stimulate the development of renewable energy sources in accordance with these concepts. This is dictated by the interconnectedness and interdependence between the two areas of development – on the one hand, the need for "green energy" to power the artificial intelligence centres requires an increase in the production and consumption of energy from renewable sources, and on the other hand, an increase in the share of unconventional energy sources necessitates increasing storage capacity and efficiency in energy use, which relies on AI.

With this study, we aim to identify the areas of application of artificial intelligence in the field of renewable energy. Applying bibliometric analysis to the totality of publications subject to our research, we identify the leading authors and highlight their most significant developments, specify the sources with the highest concentration of publications and the countries from which they originate. By conducting a keyword co-occurrence analysis, we highlight the areas in which AI is used and the purposes for which it is applied. In conclusion, we formulate conclusions about the development of the analysed leading technologies. Finally, the results of the proposed research can be used as a basis for future research and as a useful indicator of the direction of technological developments at the intersection between artificial intelligence and renewable energy sources.

II. Materials and methods

A. Literature review

The development of AI in recent years [7] has expanded the possibilities for its application in various spheres of human activity [8] - [15]. AI is used also as a lever to accelerate the development of the industry [16] - [19]. In modern times, AI is identified with "*a system's ability to interpret external data correctly, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation*" [20, p.5]. The evolution of artificial intelligence [21] offers different definitions of its essence, derived according to the achievements of computer engineers at a particular moment, and [22] they are divided into three categories, according to: (1) the methods of application of AI used, (2) the industrial application of AI and (3) the system applications of AI.

As our aim is to establish the application of AI in the field of renewable energy, in this work we do not seek to derive an authorial definition of AI and adopt the one previously proposed by [20] and cited above. However, since AI is a combination of different methods and application techniques, we will present some of the AI methods [23] in Table 1, as they also largely determine the direction of application of AI in the field of RE.

Table 1 Artificial Intelligence Methods

AI methods	Description
Machine learning (ML)	A basic AI method for machine learning, whereby by applying algorithms and models, interconnections in an existing data set are revealed and predictions are made.
Deep learning	A subset of ML specializing in hierarchical and in-depth analysis of large volumes of unstructured data through artificial neural networks.
Natural language processing	A method of understanding, interpreting, and generating human language by machines to facilitate interaction with humans.
Expert systems	AI programs mimicking the decision-making ability of experts from different fields.
Evolutionary algorithms	Algorithms exploring and refining potential solutions to complex optimization problems.
Reinforcement learning	AI reinforcement systems are an ML method in which agents are trained to make a series of decisions when interacting with a specific environment, for which they will receive a reward or penalties depending on the result obtained.
Probabilistic graphical models	A method in which, through a combination of probability theory and graphical models, a framework is created for reasoning under conditions of uncertainty and analysis of complex and complex dependencies.
Transfer learning:	A method in which a created model trained to solve a specific problem is applied as a starting point for solving another related problem.
Adversarial learning	A method for training AI to protect AI models and to assess the resilience of models.
Swarm intelligence	Method of using decentralized and self-organizing systems for collaborative problem-solving.

The cited AI training methods (see Table 1) include various techniques and strategies for solving complex and complex tasks. The application of any of the above is related to the nature of the problem encountered and the solution sought, which is why our analysis continues to identify the use of AI methods in the field of renewable energy. For the above, we will conduct bibliometric analysis and keyword co-occurrence analysis.

B. Methodology of the research

The data on which we build our research is obtained through Scopus. The large volume of critically reviewed scientific literature that the database contains provides a good basis for conducting a bibliometric analysis of the publications [24] at the intersection between renewable energy and artificial intelligence.

By applying keyword co-occurrence analysis, we establish the co-occurrence of keywords in the studied population and create networks of knowledge elements [25]. By analysing the citations of individual publications and their authors [26], we highlight the leading authors, their publications, the scientific journals in which there is the largest concentration of publications in the field under study, as well as the leading countries, authors of which have the largest number of scientific works.

To produce network maps through which we establish existing links between keywords and development trends, we use VOSviewer [27].

III. Results and Discussion

To establish the relationship between artificial intelligence and renewable energy, we analyze scientific publications in Scopus for the period 2000-2025. Our search in “title-abstract-keywords” includes the terms “renewable energy” AND “Big Data” OR “machine learning” OR “artificial intelligence” OR “Deep Learning” OR “Neural Network*” OR “Granular Computing*” OR “Evolutionary Algorithm*” OR “Semantic Rule*” OR “Genetic Algorithm*”, following the example of [26]. As a result, we received 24,963 documents, of which we excluded those that are not in English (n=767). We also limited the search according to the type of document, analysing only the results corresponding to document type “Article“.

A. Bibliometric performance analysis

Bibliometric performance analysis allows us to identify the leading authors whose research focuses on the possibilities of using artificial intelligence in renewable energy innovation. To do this, we use the metrics total number of posts and citations [24] - [28], which indicate respectively the amount of scientific production in each scientific field for the period of analysis (see Fig. 1) and the impact of this production on the scientific community.

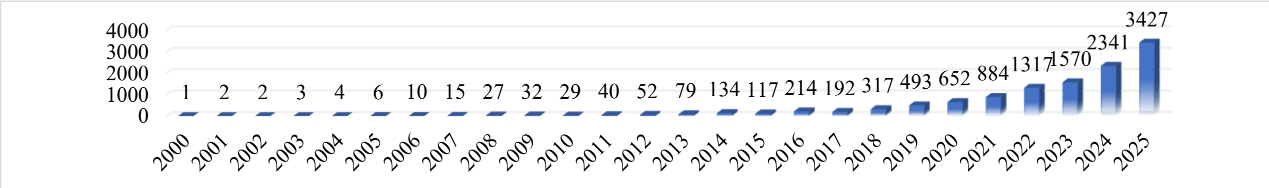

Fig. 1. Published research in Scopus in the field of RE [Own preparation based on Scopus data].

From the data constructed in this way (see Fig. 1), we establish a clearly outlined trend of growth in research activity, most pronounced in the period 2017-2025, when the number of published articles (n=7,338) increased annually by an average of 44.02%. Publications in 2025 accounted for 28.65% of all publications for the period 2000-2025, which proves the importance of the topics we have studied in modern times.

To illustrate the author's contribution to renewable energy and AI research, in Table 2 we present information about those authors who published the largest number of articles for the period 2000-2025.

TABLE 2 MOST PRODUCTIVE AUTHORS ON RE AND AI (2000-2025)

Rank	Authors	Documents	Total Citations	TC/D
1	Senjyu, T.	39	1080	27.69
2	Chen, Z..	35	2084	59.54
3	Guerrero, J. M.	29	1827	63
4	Bajaj, M. Yin, L.	25 25	754 314	30.16 12.56
5	Wang, R. Li, Y.	24 24	998 1396	41.58 58.17
6	Hu, W. Deo, R. C.	22 22	1391 1208	63.23 54.91
7	Khan, B. Sirano, P.	21 21	497 913	23.67 43.48
8	Hasanien, H .M. Wang, Y.	20 20	1023 958	51.15 47.9
9	Wang, J. Hafeez, G.	19 19	1472 1154	77.47 60,74
10	Huang, Q. Jurado, F. Ogliari, E.	17 17 17	1294 514 844	76.12 30.24 49.65

The total number of articles of the authors listed in Table 2 (416 publications) represents only 3.48% of the publication activity falling within the scope of the study (2000-2025). The fact that the most active researchers in the field of the intersection between renewable energy and artificial intelligence (see Fig. 2) make up such a small part of the population analysed testifies to the broad interest of the authors in the application of AI in the field of renewable energy.

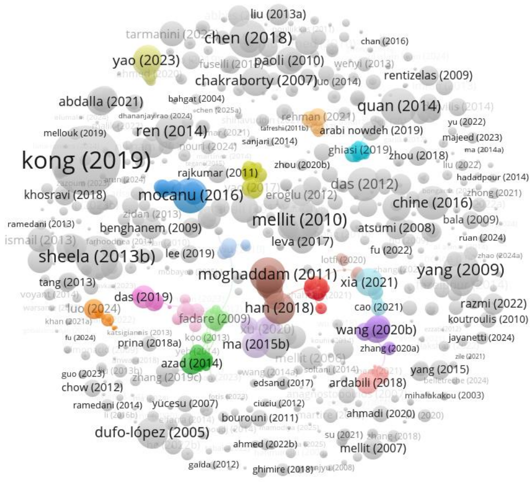

Fig. 2. Authors exploring the relationship between AI and RE [own preparation].

We are also interested in the publications that reported the highest citation rate during the analysis period, which is indicative of their importance among the academic community (see Table 3).

TABLE 3 THE 10 MOST CITED ARTICLES IN SCOPUS (2000-2025)

Rank	Articles	Total Citations
1	Short-term residential load forecasting based on lstm recurrent neural network [29].	2210
2	Review on methods to fix number of hidden neurons in neural networks [30].	838
3	A 24-h forecast of solar irradiance using artificial neural network: Application for performance prediction of a grid-connected pv plant at Trieste [31].	819
4	Model-free renewable scenario generation using generative adversarial networks [32].	659
5	Optimal design and techno-economic analysis of a hybrid solar-wind power generation system [33].	629
6	Short-term load and wind power forecasting using neural network-based prediction intervals [34].	627
7	Multi-objective operation management of a renewable mg (micro-grid) with back-up micro-turbine/fuel cell/battery hybrid power source [35].	593
8	Deep Learning for estimating building energy consumption [36].	574
9	Optimal parameters selection for bp neural network based on particle swarm optimization: A case of wind speed forecasting [37].	549
10	A novel fault diagnosis technique for photovoltaic system based on artificial neural networks [38].	526

From the information on the highest-citation publications (see Table 3), we find that the research topics are related to the possibilities of using AI for the design of systems for the production of renewable energy, prediction of RES performance, load forecasting, management of the operation of renewable micro-networks, fault diagnostic techniques, or AI can be applied in the entire spectrum of activities, related to RE.

To find out which are the scientific journals in which the authors publish their scientific achievements, we analyze those in which at least ten publications in the field of the subject we study have been published (see Table 4).

TABLE 4 THE 10 MOST PROLIFIC JOURNALS IN SCOPUS (2000-2025)

Rank	Journals	Documents	Total Citations
1	Energies	753	16187
2	IEEE Access	447	13556
3	Applied energy	430	22866
4	Energy	418	17599
5	Renewable energy technologies	327	16756
6	Sustainability (Switzerland)	252	4397
7	Energy conservation and management	198	13461
8	Journal of energy storage	197	4783
9	International Journal of electrical power and energy systems	188	7734
10	Energy reports	187	5272

The first four journals, which concentrate a significant part of the publications in the field we studied, published more than four hundred articles each for the period 2000-2025, reflecting the growing importance of research on the application of AI in the field of renewable energy. As expected, most authors have published their research in the journal *Energies,* bearing in mind that among the issues it addresses are those of technological development and engineering policy in the field of energy. In second position is *IEEE Access,* a multidisciplinary journal focused on applied engineering, innovative and experimental techniques, or research in emerging fields, which also includes research on AI and RE research. Third place is taken by *Applied energy*, whose areas of research are related to innovative solutions in the field of energy resources, their efficient and optimal utilization. The fourth position is occupied by *Energy,* whose focus is on research in the field of thermal energy and integrated energy systems, renewable energy, bioenergy, and their efficient use. The ranking is complemented by other significant journals, but due to their considerable number and our inability to present each of them in this analysis, we focus only on those with the highest recognition among researchers (see Table 4).

We complement the analysis with the publications that generated the highest citation among researchers, from which we can judge the importance of the journal for the formation and dissemination of significant innovative ideas (see Table 5).

TABLE 5 THE 10 MOST CITED JOURNALS IN SCOPUS (2000-2025)

Rank /Journals	Total Citations	Docu-ments	TC/D
1. Applied energy	22866	430	53.18
2. Energy	17599	418	42.10
3. Renewable energy technologies	16756	327	51.24
4. Energies	16187	753	21.50
5. IEEE Access	13556	447	30.33
6. Energy conservation and management	13461	198	67.98
7. IEEE transactions on smart grid	7859	77	102.06
8. International Journal of electrical power and energy systems	7734	188	41.14
9. Journal of cleaner production	6916	126	54.89
10. Energy reports	5272	187	28.19

From the data in Table 5, we can see the citation of each of the sources and the number of documents that generated these citations. Comparing the data in Table 4 and Table 5, we see the emergence of two new sources: *IEEE transactions on smart grid* and *Journal of cleaner production.* Although these journals do not have a large concentration of publications, in *IEEE transactions on smart grid* we find the highest average citation rate (TC/D = 102.06), which expresses the weight and impact of the published research. The other journals that report a higher citation rate relative to the number of published articles are

Energy conservation and management (67.98), *Journal of cleaner production* (54.89) and *Applied energy* (53.18).

Information about other sources of scientific literature and their citation can be established from Fig. 3

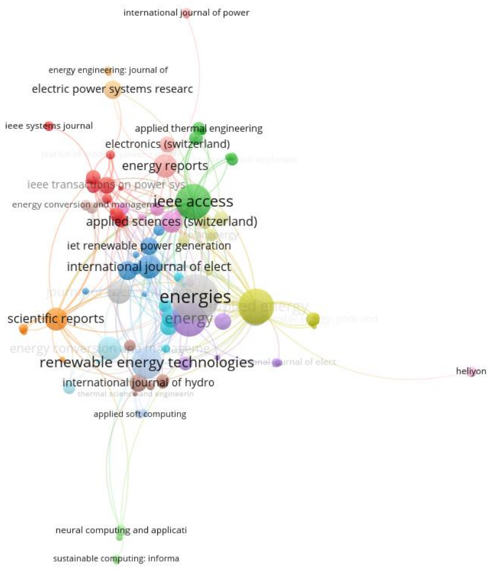

Fig. 3. Network map of most cited journals [own preparation].

To establish the contribution of the individual countries from which the analysed activity derives, we present the countries (see Fig. 4) whose authors have published the largest number of studies. The nationality of the researchers is indicative of the commitment not only of individuals, but also of society, politicians, and institutions in finding answers to questions that are significant for modern development, in this case – the relationship between AI and RE.

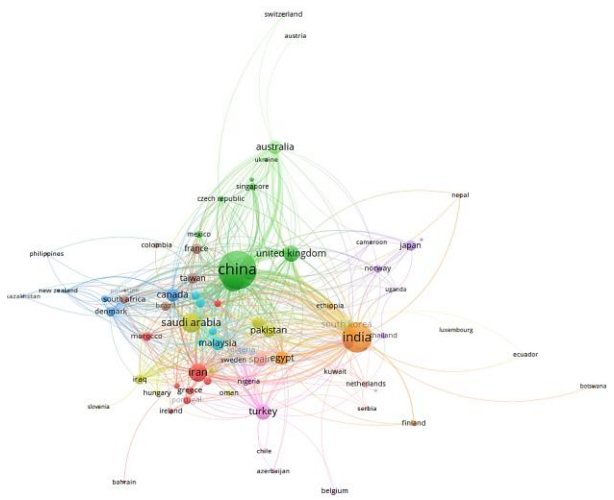

Fig. 4. Network map of sources of publication activity [own preparation].

From the network map of the countries that source publication activity (see Fig. 4), we can judge that China has made the greatest contribution to the development of research at the intersection between artificial intelligence and renewable energy (3,222 documents, 83,736 citations). In second place is India (1,972; 34,984), and in third place is the United States (1,033; 36,382). The reported three times stronger activity of authors from China, compared to those from the United States, expresses not only the efforts, but also the capacity and commitment of Chinese researchers to develop both computer technologies and those in the field of renewable energy sources. At the same time, the average citation TC/D of publications by authors from the United States is higher compared to that of authors from China (TC/D_{USA}=35.22; TC/D_{CHINA}=25.99). The ranking is complemented by countries such as: Saudi Arabia (847 articles; 20,675 citations); Iran (722; 25,078); United Kingdom (582; 20,987), Turkey (536, 12,884), etc.

B. Keywords co-occurrence analysis

When analysing the keywords indicated in the articles on which our analysis is built, we establish the thematic area in which the publications fall. We apply a “co-occurrence” analysis in all “author keywords” in a full count and use VOSviewer to create a network map of the relationships between the keywords (see Fig. 5). The total number of keywords that VOSviewer generates is 47,903, which is indicative of the wide range of topics of interest to researchers regarding the application of AI in the field of renewable energy. To clear the visual map, we only include keywords that appear more than ten times in the analysed array. This criterion is met by 2,587 keywords, of which VOSviewer calculates and visualizes 1,000, the strength of the relationships between which is the greatest. Table 6 lists the top ten keywords of the set thus defined.

TABLE 6 KEYWORD OCCURRENCES

№	Keywords	Occurrences	Total link strength
1	Renewable energy technologies	3,448	40,500
2	Renewable energy resources	2,404	31,601
3	Renewable energies	2,524	31,211
4	optimisations	2,134	28,291
5	Machine learning (ml)	2,515	28,230
6	Genetic algorithms	2,035	24,941
7	Forecasting	1,745	23,206
8	Alternative energy	1,560	21,816
9	Renewable energy sources	1,721	21,795
10	Neural-networks	1,763	20,663

With VOSviewer, we illustrate the grouping of keywords in a network map (see Fig. 5), which allows us to find the relationships between the keywords used by the authors. VOSviewer calculates the frequency with which individual keywords appear together using the association strength method. Thus, by applying algorithms, a specific distribution and grouping of keywords is sought in order to maximize the density of links in individual clusters. The size of the node indicates the frequency of occurrence of the keyword among the analysed articles.

As can be seen from Fig. 5, the keywords are divided into five clusters. The largest of them, **red cluster**, includes 247 keywords, with the most frequently appearing keywords being “renewable energies” (2524), “machine learning” (2515), “neural-networks” (1763), “forecasting” (1754), “deep learning” (1672), “wind power” (1498), “artificial neural network” (1322), “learning system” (1270), “solar energy” (1215), which expresses the application of various methods and techniques in the composition of AI to predict the productivity, efficiency gains and renewables load management.

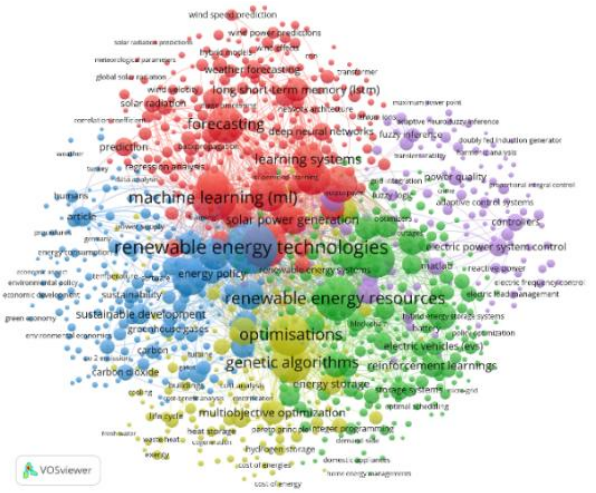

Fig. 5. Keyword Network Map [own preparation].

The second **green cluster** includes “renewable energy resources” (2404), “renewable energy sources” (1721), “microgrids” (975), “electric power transmission networks” (887), “energy management” (847), “smart power grids” (677), “reinforcement learnings” (674), as well as topics related to the application of various AI techniques to create smart grids. The third **blue cluster** covers 217 keywords, the most used of which are “renewable energy technologies” (3448), “alternative energy” (1560), “energy” (1109), “artificial intelligence” (1249), “energy utilization” (715), “decision making” (659), “algorithm” (627), “sustainable development” (553), “fossil fuels” (476) etc. The focus here is on renewable energy, in the context of the concept of sustainable development, environmental impact and waste and carbon management, as well as the application of AI to increase the efficiency of these processes and achieve the Sustainable Development Goals. The fourth **yellow cluster** covers the terms “optimisations “ (2134), “genetic algorithms” (2035), “energy efficiency” (944), “multiobjective optimization” (711) “wind turbines” (619), “energy storage” (605), “energy systems” (434), “sensitivity analysis” (323), which reveal the application of genetic algorithms for the development of alternative solutions, planning and optimization of energy storage capacity, increasing the energy efficiency of RES, cost optimization. In the fifth **purple cluster** , the emphasis is placed on “photovoltaic (pv)” (719), “particle swarm optimization (pso)” (698), “electric power system control” (409), “controllers” (394), “matlab” (376), “optimization algorithms” (335), “power quality” (302), “fuzzy system” (253), which highlights the use of artificial intelligence environments to design and simulate engineering solutions, applying fuzzy logic in AI to decision-making related to controlling, managing and optimising the operation of photovoltaic systems and other sources of RE.

To establish the trends in the development of AI applications in the field of RES, we present an overlay visualization of the keywords (see Fig. 6) used in the period 2019-2025, when we found the strongest publication activity.

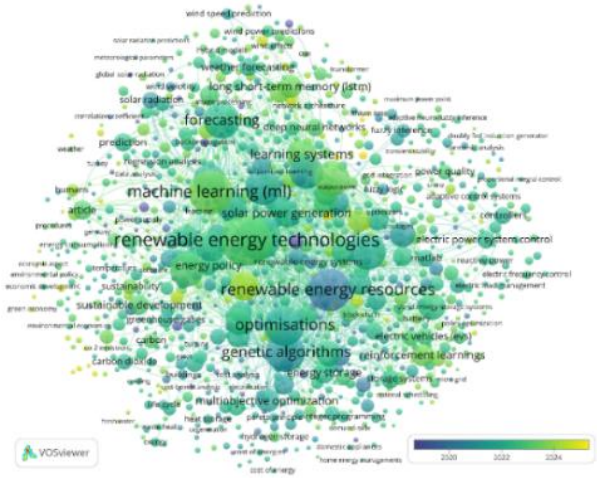

Fig. 6. Keywords overlay visualization [own preparation].

Visible from the network card, the earliest terms such as “photovoltaic cells”, “electric power generation”, “electric power system”, “optimization problems”, “algorithms”, “modelling”, “computer simulation”, “decision support system”. In 2020, researchers’ interest is focused on „renewable energy resources”, “wind”, “solar radiation”, “distributed power generation”, electric utilities”, and “genetic algorithms”, “evolutionary algorithms”, “scheduling”. For 2021, the emphasis is placed on research on the optimization of existing systems, “multiobjective optimization”, “costs”, “wind power”, “electric power transmission networks”, “solar energy”, “renewable energy sources”, and “neural-networks”, “artificial neural networks”, “fuzzy systems“, “forecasting methods”, “controllers”. In the active phase of research, in 2022, we are seeing an increase in the use of AI to predict the weather and determine the capacity of renewable sources “prediction”, “forecasting”, “weather forecasting”, “climate change”, “photovoltaics”, “wind speed”, “artificial intelligence”, “learning algorithms”, “alternative energy”, “energy efficiency”, “energy utilization”, “energy storage”, “energy management system”, “microgrid”, “sustainable development”, “digital storage”. In 2023, the focus is on renewable energy technologies affecting “carbon emission”, “energy systems”, ”hybrid renewable energy” and the possibilities for applying AI through “learning system”, “machine learning", "deep learning", "convolutional neural network", "long-short term memory", "reinforcement learnings", "deep reinforcement learnings", "predictive models". For 2024, the authors' interest is focused on energy and its sources "energy", "clean energy", "thermal", "solar fuels", "windmill", "wind power integration", "hybrid power", and, on the other hand, AI is presented through "short term memory", "wind forecasting", "adversarial machine learning". It also raises the question of „green development", „sustainable development goals", and the extent to which renewable energy meets sustainable development „zero carbon", „carbon capture and utilization", „low emission", and can contribute to the achievement of the Sustainable Development Goals.

The analysis of these topics continues into the next year, although we expect the emergence of new areas of study, due to the lack of visualization of keywords appearing more than ten times in the analysed population with a year of publication 2025.

IV. Conclusions

Through the proposed research, we have not only outlined the role of AI in the development of the renewable energy sector but also revealed some of the methods by which AI can be applied in the field of unconventional energy. As a result of the goals and objectives of the research, we conducted bibliometric analysis and keyword co-occurrence analysis, identifying the areas of application of AI in the field of renewable energy. We also highlighted the researchers and their most significant publications that found the widest response among the scientific community in the period 2000-2025.

Analysing the network map of keywords (see Fig. 5), we found that each cluster includes both different renewable energy sources and different AI methods that can be applied to increase the efficiency and operation capacity of renewable energy. This allows us to say that the scientific community is directly involved in identifying areas for application of AI in the field of RE and in revealing the advantages of implementing AI methods to increase energy efficiency.

By tracking the development trends of RE and AI research, we found that the last years of the analysed period (2019-2025) marked considerable progress in terms of areas of application of AI. Judging by the keywords overlay visualization (see Fig. 6), we formulate conclusions about the development of the application of AI in the field of RES for each individual year of the active research work of the analysed set of researchers, as follows:

- In 2019, AI is being applied in the form of algorithms and computer simulations to support the energy system.
- In 2020, through the application of genetic algorithms, opportunities are sought for optimization of the activity of renewable energy sources, creation of schedules for maximum use of solar and wind energy.
- For 2021, the issue of optimization of existing systems is deepening and multiobjective optimization is being conducted through artificial neural networks in relation to renewable energy sources. The possibility of predicting the time and controlling the operation of RES is also being investigated.
- A characteristic of 2022 is that methods for predicting weather and climate change are at the heart of the analysed research. Questions are also raised about the efficiency of management and use of RE, and the possibility of its storage. Microgrids are also considered as standalone energy grids.
- In 2023, interest in renewable energy technologies and the application of AI training systems is deepening ("machine learning", "deep learning", "convolutional neural network" "reinforcement learnings", "deep reinforcement learnings", "long-short term memory") to solve complex problems in the field of RE.
- In 2024, the authors' view goes beyond the limits of renewable energy, considering the priority consideration of the issue of clean energy, hybrid energy, zero carbon, and the Sustainable Development Goals. This is where the "adversarial machine learning" is used, which signals the commitment of researchers to create trustworthy AI systems by exploring ways to deceive and manipulate it to limit attacks and external intentional and negative impacts on RES.
- In 2025, new areas of research are emerging at the intersection between AI and BE, the development of which we will analyze in the future.

The prepared analysis and the results of the proposed study firmly emphasize the capabilities of AI to reduce the identified negative effects of RES. They can also be used as a basis for future research to identify the development of AI applications in the field of ER. At the same time, they also represent a useful indicator of the commitment of the scientific community to expand the boundaries of two of the most significant areas of development of society in recent decades.

Beyond the focus of the current study and subject to future analysis is a more detailed analysis of the publication activity conducted during the period of analysis.

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