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Review Article

Machine learning for electric power prediction: a systematic literature review

Machine learning para la predicción de energía eléctrica: una revisión sistemática de literatura

Kandel L. Yandar[1] Oscar Revelo-Sánchez[1] Manuel E. Bolaños-González[1]

[1]Departamento de Sistemas, Universidad de Nariño, San Juan de Pasto, Colombia.

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Correspondence:
kandel@udenar.edu.co

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Abstract

This study presents a Systematic Literature Review (SLR) on artificial intelligence (AI) techniques applied to electric power prediction. The specialized databases employed in this review are Scopus, IEEE, ACM, and Google Scholar. This analysis provided a perspective on the artificial intelligence techniques utilized in this field, facilitating the identification of current and emerging trends. This offers a clear understanding of upcoming opportunities to enhance accuracy in electric power prediction and decision-making.

A notable finding of this review was the predominant usage of Artificial Neural Networks (ANN) as the most prevalent technique in Machine Learning applied to electric power prediction. This preference is justified by the inherent ability of ANN to identify complex patterns and relationships in data, making them a valuable tool for electric power prediction. Additionally, the importance of essential factors in electric power prediction is highlighted, such as the significance of collecting relevant and representative data, encompassing historical and contextual information. Data preprocessing, which involves cleaning and transforming collected data to adequately prepare them for analysis and modeling, and data splitting, crucial for avoiding biases and accurately evaluating the predictive capability of the model, are also emphasized.

Resumen

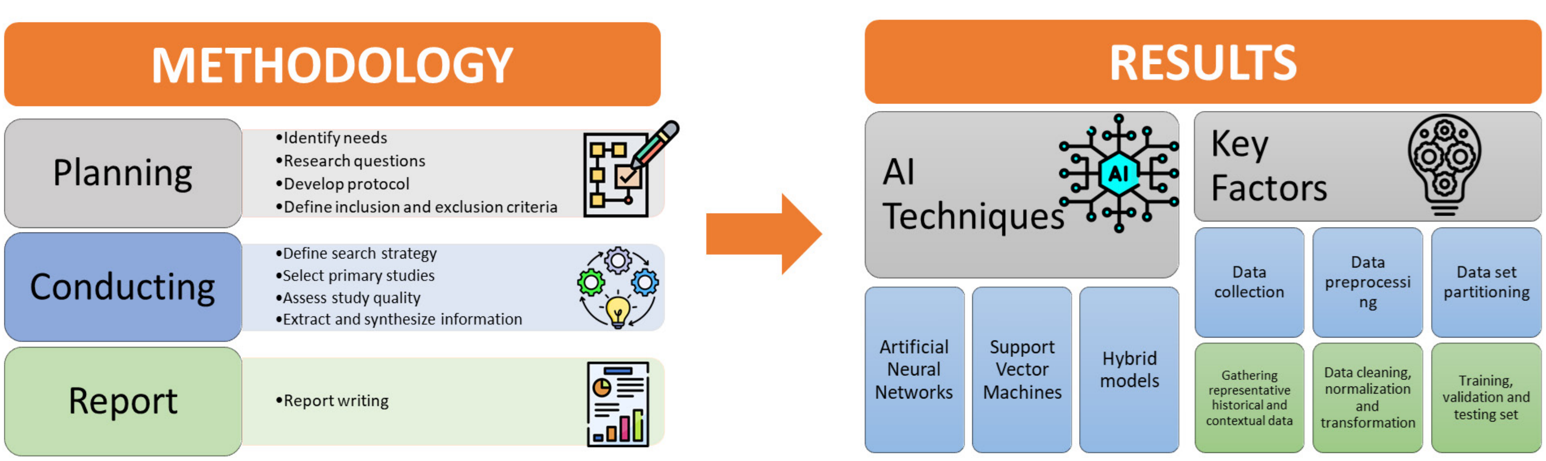
Este estudio presenta una Revisión Sistemática de la Literatura (RSL) sobre las técnicas de inteligencia artificial (IA) aplicadas para la predicción de energía eléctrica. Las bases de datos especializadas que se emplearon en esta revisión son Scopus, IEEE, ACM y Google Scholar. Este análisis ofreció una perspectiva sobre las técnicas de inteligencia artificial utilizadas en este campo, lo que facilitó la identificación de las tendencias presentes y en desarrollo. Esto proporciona una comprensión clara de las oportunidades venideras para mejorar la precisión en la predicción de la energía eléctrica y, en consecuencia, en la toma de decisiones.

Un hallazgo destacado de esta revisión fue el predominio del uso de redes neuronales artificiales (RNA) como la técnica más prevalente dentro del campo de Machine Learning aplicado a la predicción de energía eléctrica. Esta preferencia se justifica por la capacidad inherente de las RNA para identificar patrones complejos y relaciones en los datos, lo que las convierte en una herramienta valiosa para la predicción de energía eléctrica. Además, se destaca la importancia de varios factores fundamentales en la predicción de energía eléctrica, como la importancia de recolectar datos relevantes y representativos, que abarquen tanto información histórica como contextual. El preprocesamiento de datos, el cual implica la limpieza y transformación de los datos recopilados para prepararlos adecuadamente para su análisis y modelado y la división de datos, crucial para evitar sesgos y evaluar de manera precisa la capacidad predictiva del modelo.

Why was it conducted?:
Currently, the energy transition has become a key part of mitigating climate change and ensuring a sustainable and secure energy supply through the use of renewable energy sources, such as solar, wind, hydro, and geothermal. However, implementing these sources presents great challenges, especially in terms of variability and intermittency, which complicate their integration into existing energy systems. Therefore, there is a need for research on techniques to mitigate these challenges and facilitate the energy transition process. In this context, the application of artificial intelligence (AI) techniques has become essential as AI can significantly improve the predictive accuracy of power generation and support informed decision-making in a sector that is constantly evolving

What were the most relevant results?
TThe study highlights that the most widely used artificial intelligence (AI) technique for electric power prediction is Artificial Neural Networks (ANNs). These networks are highly valued due to their ability to identify complex patterns and subtle relationships in large volumes of data, allowing them to make accurate predictions and adapt to various operating conditions.
In addition, the study underscores the crucial importance of several factors in improving the accuracy and efficiency of predictive models. First, it is essential to collect representative historical and contextual data, as a robust and well-structured database provides the necessary foundation for training AI models. This data should encompass a variety of relevant variables, including energy consumption patterns, weather conditions, and other contextual factors that may influence energy generation and demand. Data preprocessing also stands out as a critical factor. This process includes data cleaning to remove inconsistencies and errors, normalization to ensure that all variables are on a comparable scale, and data transformation to highlight the most relevant features. Proper preprocessing ensures that the data fed into the ANNs are of high quality, thus improving the model's accuracy. Finally, the study emphasizes the importance of a correct division of the dataset into training, validation, and test subsets. This division allows the model to be evaluated and adjusted effectively, ensuring that it does not overfit the training data and that it can generalize well to unseen data.

What do these results contribute?
The systematic literature review provides insight into current and emerging trends in the use of artificial intelligence (AI) for energy forecasting. This approach not only identifies future opportunities for the development of more advanced and efficient techniques but also establishes a solid foundation for further research and practical applications. By compiling and analyzing previous research, it facilitates the creation of innovative solutions to contemporary energy challenges. The results of this review provide a clear understanding of the most effective AI techniques for electric power prediction, which can significantly improve prediction accuracy and optimize energy resource management. This improvement in prediction accuracy enables energy managers to make more informed decisions, contributing to more efficient and sustainable management of energy systems. The importance of operational skills and agribusiness integration. Furthermore, they highlight the growing relevance of marketing and innovation activities, which suggests that strategies focused on these areas can be crucial to improving competitiveness. This information can be used by actors in agroindustrial chains, policymakers and academics to develop more effective strategies that maximize value generation and improve the efficiency and sustainability of the agroindustrial sector.



Graphical Abstract

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Introduction

Power generation is vital to meet society's energy needs. However, traditional sources are diminishing, which could lead to an energy crisis due to their scarcity. Therefore, it is imperative to look for new sources of energy. In this regard, a steady increase in the use of renewable energy sources has been observed, which poses new challenges to ensure the reliable and high-quality delivery of services in the power distribution network.

The use of AI techniques to analyze and optimize power generation and consumption has become essential to optimize the use of renewable energy resources. By analyzing historical and real-time data and considering external variables, a deeper understanding of the energy market is gained, which supports informed decision-making.

In an industry where conditions are constantly changing, this anticipatory capability provided by AI techniques becomes an invaluable resource that not only enables adaptation but also leadership in a competitive and complex environment.

Machine Learning represents a fundamental sub-discipline within the field of artificial intelligence. Its operation is based on algorithms that learn from data, making decisions like human cognitive processes (1). This capability has acquired an essential role in electric power prediction, where the application of models supported by AI techniques, such as artificial neural networks, has proven to be an important tool in this field.

In this sense, the theoretical contribution of this research lies in the collection and analysis of previous research in the discipline of AI applied to electric power prediction. This SLR article allows identifying trends, advantages and limitations of AI techniques applied to electric power forecasting, playing a crucial role in the transition towards a more sustainable energy system, by providing an understanding of AI techniques used to optimize energy management.

On the other hand, the methodological contribution of this review is directed to the description of the method used to select, analyze, and synthesize the relevant literature in the field. By following a systematic and transparent approach, the SLR ensures the validity of the results obtained. This methodological rigor allows researchers and practitioners in the disciplines of systems engineering, electrical engineering, and environmental engineering to rely on the conclusions derived from the synthesis of scientific evidence and provide a starting point for the generation of solutions aimed at addressing contemporary environmental challenges more effectively and accurately.

The article is divided into 4 sections, as follows: section 1 provides a brief introduction; section 2 details the research method employed; the results and discussion are presented in section 3; and the conclusions are presented in section 4.

Methodology

This SLR was carried out by adapting the methodological strategy of Zapata and Baron (2), which is based on the SLR process proposed by Kitchenham and Charters (3). Figure 1 describes the phases and activities developed for this review.

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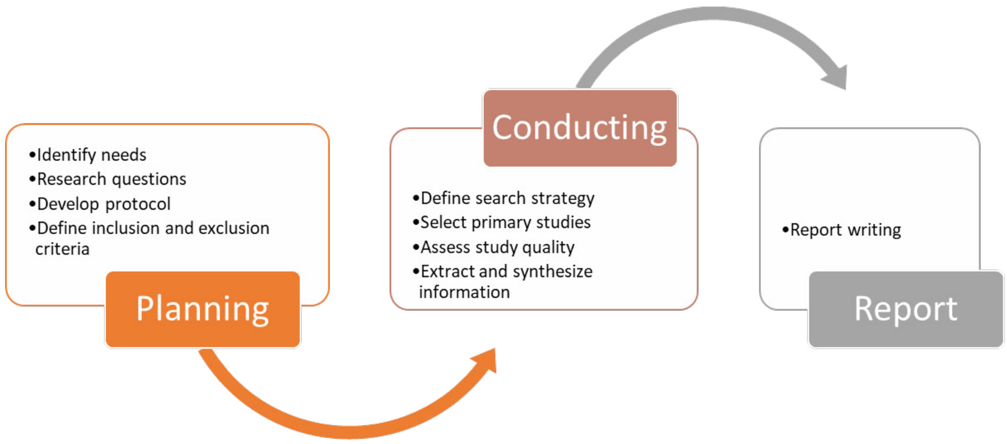

Figure 1. SLR process

Planning

Identifying the needs of the SLR

Conducting an SLR on artificial intelligence techniques used in electric power prediction allows for identifying, analyzing, and compiling the relevant literature associated with this field. These findings will provide a solid foundation that can be shared with the scientific community.

Specifying research questions

For Kitchenham and Charters (3) the crucial activity lies in the elaboration of the research questions, which serve as a guide for the development of the search activities of the primary studies as well as for the extraction and synthesis of information.

In this research, two questions are posed, which are detailed below:

RQ1. What AI techniques are used for electric power forecasting?

RQ2. What are the key factors used for electric power prediction?

Developing the protocol

The following procedures are applied in the execution of this SLR: (i) identification of relevant and appropriate study sources for the investigation; (ii) development of search strings, to identify potential studies to be included in the analysis; (iii) definition of inclusion and exclusion criteria to discern relevant studies for the investigation.

Defining inclusion and exclusion criteria

The purpose of defining these criteria is to select the relevant literature for the research by establishing clear and specific limits for the selection of relevant studies to be included in the analysis. In this context, the specific criteria for this review are detailed in Table 1.

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Table 1. Inclusion and exclusion criteria

INCLUSION CRITERIA
Time window (2013 - 2024).
Studies that relate to artificial intelligence techniques used for electric power prediction.
Title of the paper related to artificial intelligence techniques used in the context of electric power.
Keywords related to the research.
EXCLUSION CRITERIA
Research in a language other than English or Spanish is not considered.
Duplicate articles.
Literature reviews or mappings are not taken into account.

The definition of the time window over 10 years took into account that the field of artificial intelligence (AI) and prediction techniques have undergone significant advances in the last decade. Therefore, extending the review period allows us to capture the development and evolution of various techniques, offering a more complete view of how they have improved, how they have adapted to new needs, and how new proposals and challenges have arisen in the energy sector.

Conducting the RSL

Once the protocol has been defined, the implementation of the SLR is divided into four activities, which are detailed below:

Search strategy

Within the framework of this research, the use of search strings is included. According to Zapata and Baron (2), "Search strings are configurations that describe the research questions. These strings are the criteria entered in the search engines of digital sources."

The search string for the SLR on AI techniques used in the context of electrical energy is the following: ("artificial intelligence techniques") AND ("energy trading" OR "energy transaction" OR "energy exchange" OR "energy management").

Selecting primary studies

The objective of this activity is to select the relevant studies that contribute to answer the defined research questions (3).

Identify sources of studies

The literature search on AI techniques used in the context of electric power is performed using digital bibliographic databases such as SCOPUS, ACM Digital Library, IEEE Xplore Digital Library, and Google Scholar. The results of this search are presented in Figure 2.

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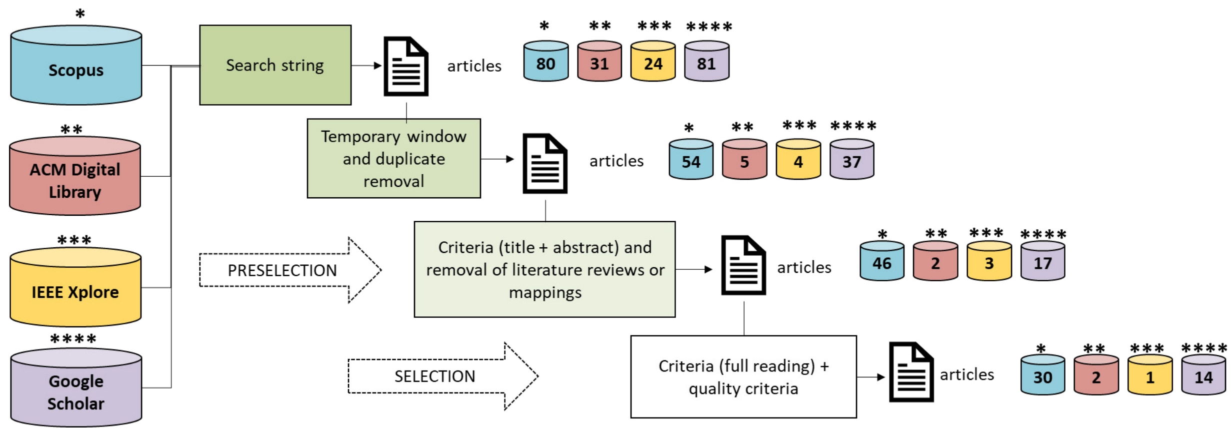

Figure 2. Results of the study sources

Selecting studies

A set of 216 potentially relevant bibliographic records was found using the search string defined in activity 1.2.1 in the four previously selected bibliographic sources. Subsequently, a purification process was carried out covering the time window between 2013 and 2023, as well as the elimination of duplicates, resulting in a total of 100 records. Within this purified selection, we proceeded to examine both the titles and abstracts of the articles to identify those that directly addressed AI techniques used in the context of electric power. As a result of this analysis, 68 records were highlighted and subjected to a full review.

Assessing study quality

To ensure quality in the selection of studies, four fundamental criteria established by Collazos et al. (4) are applied. These criteria include the relevance of the content to address the questions posed in the review, clarity in the definition of the research objectives, adequate description of the context in which the study is carried out, and a clear presentation of the results, which encompass three essential aspects of quality: the establishment of a minimum level of quality, the credibility and relevance of the studies.

Quality was assessed by analysis of the 68 complete records, followed by an evaluation of the degree of adherence to the pre-established criteria. From this process, a final set of 34 documents was identified as the main sources of information for the SLR. These documents are listed in Table 2 along with their bibliographic references, organized chronologically by year of publication.

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Table 2. Documents reviewed

Year	No	Reference
2013	2	(5), (6)
2014	0	
2015	1	(7)
2016	3	(8), (9), (10)
2017	3	(11), (12), (13)
2018	3	(14), (15), (16)
2019	3	(17), (18), (1)
2020	4	(19), (20), (21), (22)
2021	7	(23), (24), (25), (26), (27), (28), (29)
2022	3	(30), (31), (32)
2023	16	(33), (34), (35), (36), (37), (38), (39), (40), (41), (42), (43), (44), (45), (46), (47), (48)
2024	2	(49), (50)

Extraction and synthesis of results

The final stage of the process focused on data extraction to answer the previously defined research questions, as well as on the synthesis of the results. From the selection of documents, extractions of specific metadata, extracted from the bibliographic records, were carried out.

This metadata includes details such as title, year of publication, source of publication, authors, and country of institutional affiliation at the date of publication of the article, focusing on AI techniques applied in the field of electric power. To facilitate the understanding of the study, a classification of the terms techniques and models is made, considering that the articles reviewed use them interchangeably. An extract is presented in Table 3.

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Table 3. Data extraction

Author	Technique / Model	Relevant factors	Contribution
(29)	Artificial neural networks (ANN) and Support vector machine (SVM)	1. Data collection (energy and meteorological data for 2 years). 2. Data preprocessing 3. Data set partitioning (training, testing, and validation).	Two AI techniques Artificial neural networks (ANN) and Support vector machine (SVM) are used to predict the peak energy demand to estimate the energy usage for an office building on a university campus based on weather data and historical energy data.
(30)	Decision Trees	1. Data collection (time, price, and temperature during 1 year). 2. Preprocessing 3. Data set partitioning (training and testing).	The implementation of technologies such as the Internet of Things (IoT) and machine learning for energy management and conservation in buildings using the Decision Trees technique is proposed.
(22)	Support vector machine (SVM) and Artificial neural networks (ANN)	1. Data collection (historical consumption data). 2. Data set partitioning (training, testing, and validation)	It proposes the prediction of energy consumption in residential buildings, using Support Vector Machine (SVM) and Radial Basis Functions Neural Network (RBFNN).
(18)	K-means and Artificial neural networks (ANN)	1. Data collection (building energy use, meteorological data). 2. AI development 3. Model implementation Scenario analysis	It proposes the prediction of energy consumption on campus using the K-means and long-short-term memory (LSTM) technique.

The completeness of this research is available at the following link: dataextraction.pdf. Figure 3 depicts various AI techniques/models that are used in the context of electric power.

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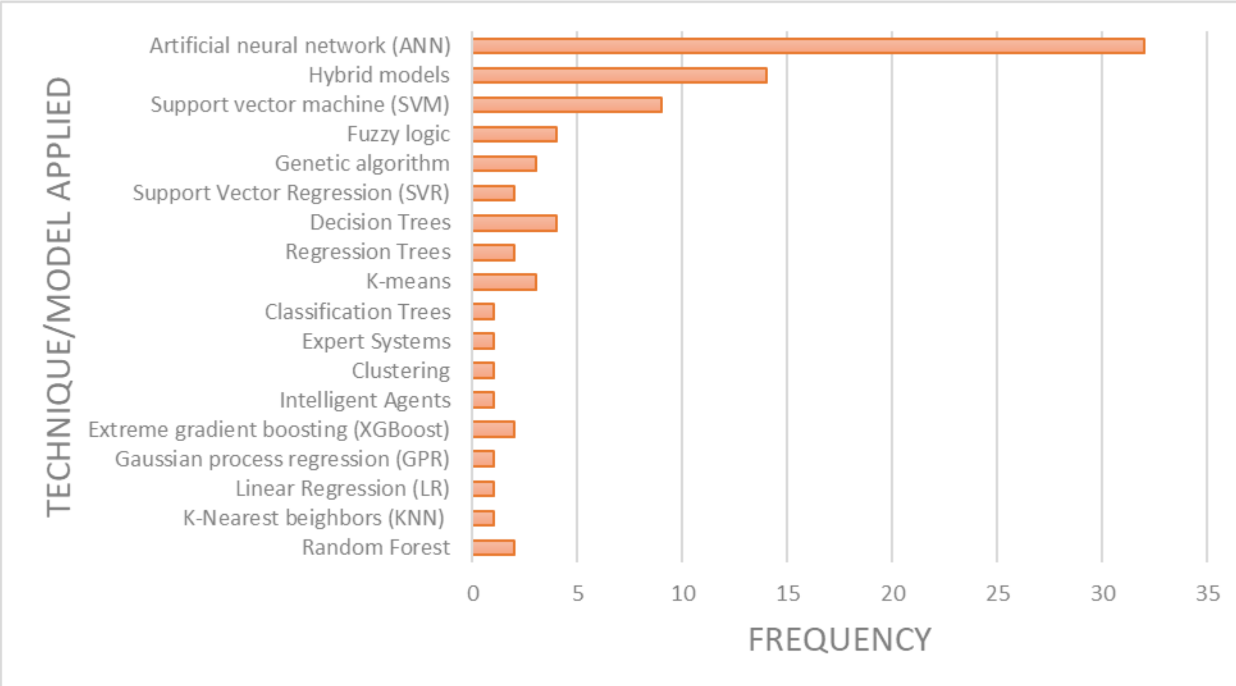

Figure 3. Applied techniques/models

SLR Reporting

The conclusive stage of a systematic review involves writing up and disseminating the findings of the review to the relevant community (3). This report is presented in the results section of this article.

Results and discussion

A detailed analysis of the different AI techniques employed in electric power forecasting was carried out. Machine Learning was found to be the most widely adopted sub-discipline of artificial intelligence, thanks to its ability to model complex relationships, handle large data sets, and perform forecasts spanning various time intervals.

In addition, among the most prominent techniques used for power forecasting are ANNs, hybrid models, and support vector machines. These techniques have proven to be essential pillars in energy analysis and forecast generation.

It is relevant to note that most of the studies analyzed employ ANNs in environments such as buildings or residential houses oriented to the optimization of energy consumption. These networks facilitate the prediction of peak demand and allow automatic adjustment of energy distribution to maximize efficiency and reduce costs. In addition, university campuses play a crucial role in the development of these predictive techniques, enabling the efficient management of energy consumption in multiple buildings and services by integrating data from various sources, such as weather conditions and facility usage patterns. This not only drives sustainability but also provides an invaluable research platform for students and professionals. Finally, microgrids emerge as a significant area for the application of ANNs, as they facilitate the integration of renewable energy sources into the power grid. By predicting variations in solar and wind power generation, and adjusting demand to these changes, they contribute to the creation of a more resilient energy infrastructure that is prepared to respond to the needs of an expanding urban population. This preference is supported by their inherent structure for identifying patterns and relationships in data, which makes them uniquely suited to address a variety of challenges. Their ability to model and forecast these behaviors with greater accuracy compared to conventional methods positions them as a very useful tool in this area.

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Furthermore, it is consistently evidenced that data collection, preprocessing, and data partitioning (training, testing, and validation) are important aspects in most studies when dealing with obtaining information related to the relevant factors for the realization of electric power prediction models. These factors are established as the basis for ensuring the quality and reliability of such models.

Finally, the research questions established in activity 1.1.2 of the planning phase of this review are answered below.

RQ1. What AI techniques are used for electric power prediction?

After analyzing the results obtained, it is clear that the most used artificial intelligence techniques are within the Machine Learning field. In particular, the application of artificial neural networks stands out as an approach of high relevance in this context, and this is due to several inherent attributes that make them particularly suitable for addressing a wide variety of challenges in electric power prediction.

Artificial neural networks, being widely preferred, are distinguished by their intrinsic ability to discern patterns and relationships in data. This trait is particularly valuable when it comes to forecasting both power generation and consumption. In addition to this pattern detection prowess, these networks also can model complex, nonlinear relationships, which is essential in the context of electric power, where variables may be interconnected in intricate ways.

In the context of electric power forecasting, artificial neural networks stand out as the most commonly employed and effective technique, playing a crucial role. Their ability to provide accurate forecasts tailored to the complexity of the energy sector positions them as a central element for the successful implementation of artificial intelligence solutions in this domain.

On the other hand, support vector machines (SVM) and hybrid models stand out as additional alternatives for the development of electric power forecasting models, depending on the application context. SVM are especially useful for handling nonlinear problems, as they transform data to higher dimensional spaces where they become linearly separable through the use of appropriate kernels. This allows SVM to generalize well, making them less prone to overfitting compared to other more complex models. Their application excels when a small data set is available for training. In the case of application, hybrid models are shown to improve accuracy and overall system performance by combining different techniques, adapting to a wide variety of problems and data types, and providing versatile and adaptable solutions, but they are more demanding in terms of computational resources and processing time.

RQ2. What are the key factors used for power forecasting?

Electric power forecasting involves taking into account a variety of key factors that are fundamental to obtaining accurate and reliable forecasts. In most of the studies reviewed in this SLR, the importance of factors such as data collection is highlighted as the fundamental basis for effective analysis and modeling, which allows for capturing patterns and trends with greater accuracy. Likewise, correct data preprocessing ensures data consistency and uniformity, and the division of the dataset into training, validation, and testing subsets emerges as a fundamental phase to assess the performance of the predictive model. These aspects are considered essential elements in the electric power prediction process, serving as fundamental pillars to ensure the effectiveness and accuracy of the results obtained.

Conclusions

In this study, an SLR methodology was used to collect, analyze, and synthesize research advances relevant to the field of study. Initially, 216 potentially relevant bibliographic records were identified using the search string defined in activity 1.2.1. Once the purification process was completed and taking into account the previously defined inclusion and exclusion criteria, 68 records were selected and subjected to a complete review. Of these, 47 papers were included as the evidence base used to answer the two key questions established. The SLR highlights that, in electric power prediction, the most widely used AI techniques are within the Machine Learning domain, specifically the use of ANNs emerges as the most prevalent and effective technique. Their ability to identify patterns and relationships in data makes them an especially valuable choice in power forecasting.

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The proper execution of factors such as data collection, preprocessing, and data partitioning proves to be a highly relevant element in the process of developing a predictive model. These steps not only improve the model's performance but also ensure the accuracy and quality of the resulting predictions. Therefore, their correct execution is essential to obtain reliable and significant results in the prediction domain.

The implementation of the methodological strategy ensures that the results obtained constitute a robust foundation that can be shared with the scientific community.

Through the development of this systematic review, it is possible to provide the scientific community with an overview of the research on the use of Artificial Intelligence techniques/models, specifically in the field of Machine Learning used for electric power prediction, in addition to showing the growing number of publications and a variety of approaches to address the topic. This, as mentioned above, can be exploited to open up significant new opportunities for future research.

Considering that artificial neural networks (ANNs) represent the most widely used Machine Learning technique/model for prediction in the electric power sector and considering that the application spectrum of ANNs is very broad, it would be fruitful to conduct a detailed study on the specific types of ANNs employed in this field as a line of future research.

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