

Review Article

Int J Energy Studies 2026; 11(2): 1655-1677

DOI: 10.58559/ijes.1899422

Received : 28 Feb 2026

Revised : 11 May 2026

Accepted : 15 May 2026

## Global trends in nuclear energy forecasting: Methodological analysis, bibliometric evidence and strategic-geopolitical dimensions

Esranur Çelebi <sup>a\*</sup>, Hüseyin Koçak <sup>b</sup>

<sup>a</sup>Quantitative Methods Division, Pamukkale University, 20160 Denizli, Turkey, ORCID : 0000-0002-7840-2398

<sup>b</sup>Quantitative Methods Division, Pamukkale University, 20160 Denizli, Turkey, ORCID : 0000-0001-9683-6096

(\*Corresponding Author: [esra09393@gmail.com](mailto:esra09393@gmail.com))

### Highlights

- The study analyzes the evolution of nuclear energy forecasting from traditional econometrics to AI-driven models.
- This research provides the first integrated analysis of bibliometric mapping, methodology, and geopolitical context.
- Nuclear energy forecasting is established as a strategic decision-support tool for global energy security.
- The findings emphasize the future role of explainable artificial intelligence and scenario-based policy simulations
- The proposed framework serves as a comprehensive reference for designing sustainable and low-carbon energy systems.

**You can cite this article as:** Çelebi E, Koçak H. Global trends in nuclear energy forecasting: Methodological analysis, bibliometric evidence and strategic-geopolitical dimensions. Int J Energy Studies 2026; 11(2): 1655-1677.

### ABSTRACT

The aim of this study is to reveal global trends in the production and consumption of nuclear energy. It will also compare econometric, machine learning and hybrid models using common criteria. Furthermore, it will evaluate bibliometric findings within a strategic-geopolitical context. The study covers 36 research articles published between 1 August 1996 and 11 November 2025. Data were collected from the Web of Science Core Collection (WoSCC), Dimensions and PubMed databases, and analyses were performed using VOSviewer and Biblioshiny software. 66.7% of the publications were produced after 2011, a period which accounted for 96.5% of the total citations. Overall, 1,117 citations and an h-index of 17 were obtained. On a country basis, the highest production (15 publications) belongs to China. The findings also demonstrate that, since 2011, machine learning-based approaches, such as Support Vector Regression (SVR) and Long Short-Term Memory (LSTM), have emerged as dominant, progressing in parallel with the energy security and decarbonisation agenda. This study provides an evidence-based framework for selecting methods and planning policies for forecasting nuclear energy.

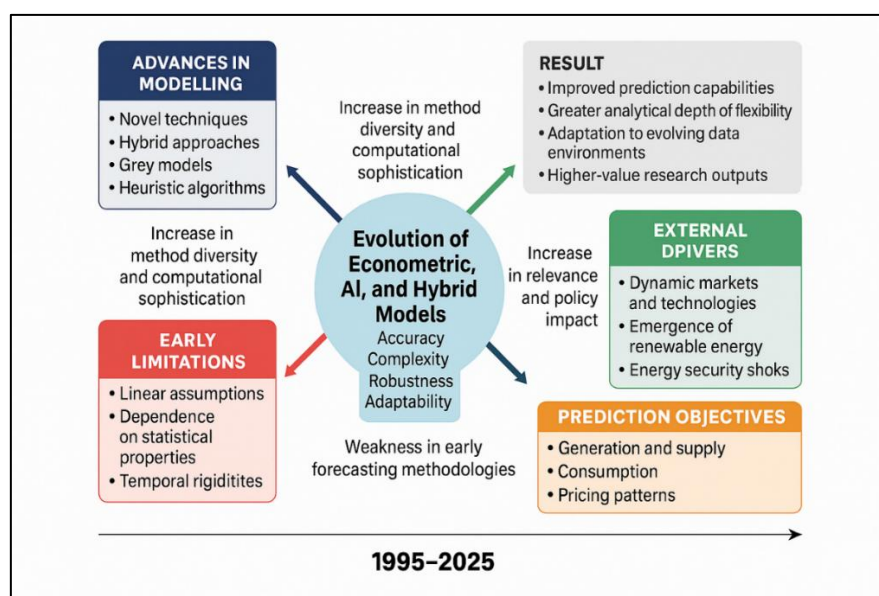
**Keywords:** Nuclear energy, Forecasting, Bibliometric analysis, Research trend, Collaboration network

## 1. INTRODUCTION

Forecasting nuclear energy production and consumption is a strategic tool within the 'triple dilemma' (security, cost and decarbonisation) of energy systems today. While accelerating electrification and the rising demand profile of data centres indicate that electricity demand will grow faster than total energy demand, decisions regarding low-carbon capacity must be based on robust forecasts as the share of variable renewables increases. This trend is clearly highlighted in the International Energy Agency's (IEA) 2024 Outlook and in its current electricity demand forecasts [1-3]. However, when planning systems, both unit and system costs/values (e.g. backup, balancing and grid costs) are important. Comparative analyses by the Nuclear Energy Agency (NEA) show that it is possible to achieve low-carbon targets with minimal system costs by combining nuclear and wind/solar energy [4,5]. Since climate-induced heatwaves and water/cooling constraints can periodically limit nuclear production, it is also critical to reflect these effects in operational and probabilistic (non-deterministic) [6-7]. In terms of financing and policy, the European Union's decision to include nuclear energy under certain conditions in its Sustainable Finance Taxonomy, and the subsequent court approval of this approach in 2025, has helped to clarify the investment framework [8]. Regarding fuel, price increases and volatility in the uranium market, especially in the enrichment sector, are making long-term contract strategies more relevant again [9,10]. For these reasons, reliable and explainable nuclear forecasts are needed in the short, medium and long term for maintenance/fuel cycle synchronisation, supply adequacy, Small Modular Reactor (SMR) sequencing/site selection and portfolio optimisation on net-zero paths. Probabilistic (as opposed to deterministic) forecasting and method comparisons (using econometrics, machine learning (ML) and hybrid approaches) are becoming increasingly prevalent in the literature. It is suggested that good practice standards, such as providing forecast ranges and ensuring explainability, need to be established [11,12]. These global developments have made it necessary to systematically evaluate the evolution of academic studies on nuclear energy forecasting in terms of both content and methodology (see Figure 1).

The bibliometric analysis approach provides an opportunity to objectively and comparably examine the structural dynamics of the field. This method is effective for examining the historical development, structural characteristics and interaction networks of literature through quantitative indicators. It makes it possible to evaluate production dynamics, trends and areas of deficiency in a particular research field from an interdisciplinary perspective. As frequently emphasised in academic studies by Jia et al. [13], Li and Hale [14], and Li and Zhao [15], bibliometric analysis

plays a critical role in revealing knowledge production networks and methodological changes in the energy field. This study aims to visualise methodological and policy transformations in nuclear energy forecasting by analysing 36 articles published between 1996 and 2025 in the WoSCC, Dimensions, and PubMed databases. The findings show that the field of study has gradually evolved from classical econometric models (e.g. ARIMA and VAR/VECM) to grey systems (GM(1,1)) and, finally, to AI-based hybrid models (e.g. artificial neural networks (ANNs), support vector regression (SVR) and long short-term memory (LSTM)). Key turning points that triggered this evolutionary process include the Fukushima accident, the Paris Climate Agreement, and the 2021–22 energy crisis.



**Figure 1.** Strategic and methodological overview for nuclear energy forecasts.

## 2. THE METHOD

### 2.1. Data Sources and Search Strategy

This study adopted a multi-database literature search strategy to ensure a balanced and reproducible representation of nuclear energy forecasting research. The Web of Science Core Collection (WoSCC), Dimensions and PubMed databases were selected because they provide complementary coverage of indexed publications, citation records and interdisciplinary research outputs. WoSCC offers a standard basis for long-term trend and impact analyses through curated citation indexes such as SCIE, SSCI, AHCI and ESCI [16,17]. Dimensions provides a broad research graph integrating publications, citations, grants, patents and policy documents [18], while

PubMed was included due to its MEDLINE/MeSH infrastructure and its relevance for health, environmental and energy-related aspects of nuclear technologies [19,20].

The search strategy was designed to identify studies directly related to nuclear energy forecasting rather than broader studies on nuclear policy, nuclear safety, radiation or general energy modelling. The keywords were grouped into two categories: (i) nuclear energy and forecasting terms, including “nuclear energy”, “nuclear power”, “forecast\*”, “predict\*” and “projection”; and (ii) forecasted variables, including “consumption”, “production”, “demand”, “supply” and “generation”. These terms were combined using Boolean operators, field codes and wildcards. A representative search string was: (“nuclear energy” OR “nuclear power”) AND (“forecast” OR “predict” OR “projection”) AND (“consumption” OR “production” OR “demand” OR “supply” OR “generation”)\*\*.

The search was limited to English peer-reviewed research articles published between 1996 and 2025. Reviews, conference papers, editorials, book chapters, duplicate records and studies without a forecasting-oriented methodological framework were excluded. Records were screened by title, abstract and keywords, followed by full-text assessment. As a result, 36 methodologically relevant articles were included in the final bibliometric analysis. Although this number is limited, it reflects the focused scope of the study and the relatively specialized nature of nuclear energy forecasting literature. Future studies may expand the dataset by including Scopus, broader keyword combinations and additional publication types.

## **2.2. Bibliometric Parameters and Analysis Settings**

In bibliometric network analyses, parameters were standardised to ensure reproducibility and comparability of the results. This study used the fractional counting method; the LinLog/modularity approach — the default setting of VOSviewer — was preferred for normalisation. The minimum co-citation threshold was set at two, and the minimum number of keyword repetitions at three. In the author-level analysis, the criterion of having at least two collaborative publications was applied, as well as having at least three publications at the national level. The review period covers the years 1996–2025. The analysis included co-authorship, co-citation, co-occurrence and bibliographic coupling network types; the association strength algorithm was used. All parameters were determined in accordance with the standards suggested

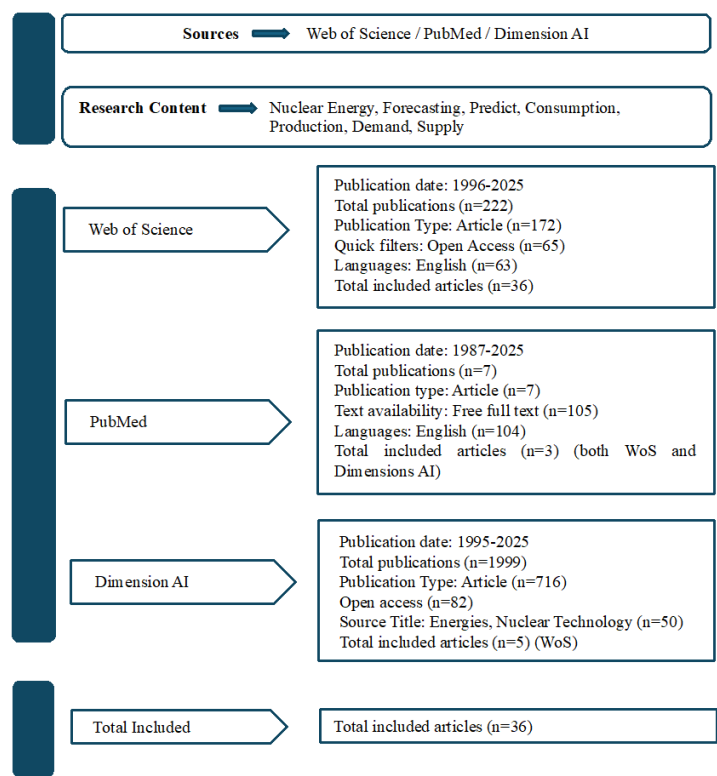
in the literature [21,22] and low-frequency elements were filtered to highlight strong relationships visually.

### **2.3. Study Selection, Data Cleaning and Dataset Limitations**

In this study, literature selection was conducted in accordance with the PRISMA flowchart framework. Peer-reviewed research articles focusing directly on nuclear energy forecasting in relation to production, consumption, demand, supply or generation were included in the analysis. In contrast, review articles, conference proceedings, editorials, book chapters, non-English publications and duplicate records were excluded. Broader studies on nuclear energy policy, nuclear safety, radiation, nuclear technology or general energy modelling were also excluded unless they explicitly included a forecasting-oriented methodological framework.

After the initial retrieval, duplicate entries were removed through title, author, publication year and DOI matching. The remaining records were screened by title, abstract and keywords, followed by full-text assessment to determine their methodological relevance to nuclear energy forecasting. Following this multi-stage selection process, 36 methodologically suitable research articles were included in the final bibliometric analysis (see Figure 2).

Although the final dataset consists of a relatively limited number of publications, this reflects the highly specific and focused scope of the study rather than a lack of search coverage. The dataset represents a coherent body of literature directly related to nuclear energy forecasting. Nevertheless, this limited number should be acknowledged as a limitation of the study. Future research may expand the dataset by incorporating additional databases such as Scopus, IEEE Xplore or Google Scholar, broader keyword combinations, conference proceedings and grey literature in order to provide a more comprehensive mapping of the field.



**Figure 2.** PRISMA flow diagram.

### 2.4. Inclusion and Exclusion Criteria

In this study, literature selection was conducted in accordance with the PRISMA flowchart framework. Peer-reviewed research articles focusing on production, consumption and demand forecasting in the nuclear energy sector were examined from the data sources. Review articles, conference proceedings and publications in languages other than English were excluded, as were duplicate entries, which were removed through normalisation. Following this multi-stage selection process, in the final analysis, 36 methodologically suitable studies were included (see Figure 2).

## 3. FINDINGS

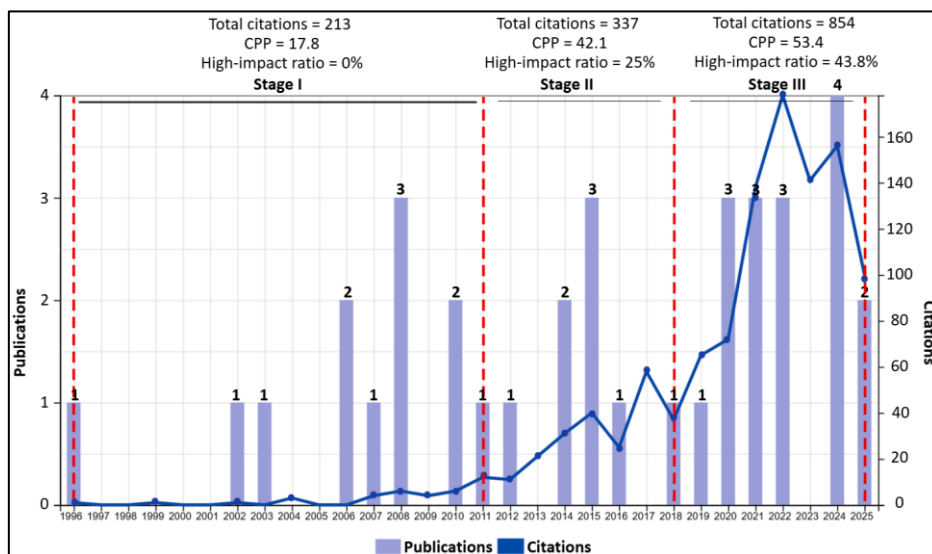
### 3.1. Annual Trends in Publications

The development of nuclear energy forecasting research can be divided into three main phases: Stage I (1996–2011) is the 'establishment period', Stage II (2012–2018) is the 'consolidation period', and Stage III (2019–2025) is the 'acceleration and maturation period' (see Figure 3). Throughout this period, literature shows significant maturation in terms of quantitative growth, methodological diversification and scientific impact. During Stage I (1996–2011), publications were infrequent (with 0–1 article published per year in most years), resulting in a total of 213

citations and an average CPP value of 17.8. During this period, studies focused on country-specific applications and classical econometric/time series methods (ARIMA, GM and VAR/VECM). In Stage II (2012–2018), the number of publications increased to eight, the number of citations rose to 337 and the CPP value increased to 42.1. This period was a transitional phase in which early hybrid and machine learning-based models emerged alongside an increase in open data and computational capacity. Stage III (2019–2025) represents a period of maturation where methodological transformation merges with political and economic driving forces. During this period, 16 articles were published, receiving 854 citations and achieving a CPP value of 53.4; the high-impact publication rate reached 43.8%. The increasing volume of publications and citations indicates that, from the 2020s onwards, the field has evolved from an academic research area to a decision-support function in energy planning, forecasting and policy design. This momentum developed in parallel with the transformation of global energy policies, with the adoption of SVR, LSTM, optimisation algorithms and hybrid artificial intelligence models directly responding to the new requirements of energy systems. The peak year of 2022 came immediately after the global energy crisis that followed the Russia–Ukraine war. During this period, nuclear energy once again became strategically important in terms of energy security and supply continuity. These developments created a threshold where methodological advancements intersected with political priorities, taking the field of nuclear energy forecasting to a new level of maturity in terms of academic visibility and strategic decision-support capacity.

The evolution of the field in terms of methodological innovation and data intensity is reflected in Table 1, which features studies with the highest number of citations in the area of nuclear energy forecasting. The hybrid ensemble learning model developed by Tang et al. [23] is a pioneer in machine learning-based forecasting approaches, having received 151 citations. Studies by Wu et al. [24] and Ding et al. [25] have demonstrated the high accuracy of energy forecasting using grey systems (Grey Models) and artificial intelligence-based adaptive models. Yue et al. [26] examined the relationship between carbon taxes, renewable energy and sustainable development, contextualising the field within environmental policy. After 2018, there has been a rapid increase in publications combining grey system derivatives (e.g. FAGMO, Riccati and adaptive grey) with machine learning and optimisation. The significant increase in citation averages during this period indicates that the field's scientific visibility has strengthened. Furthermore, as the majority of studies are based on Chinese energy economy data, regional concentration can be said to have

become a focus point in the global production of knowledge regarding nuclear energy forecasting. On the other hand, Grover and Chandra [27] have studied the electricity forecasting for India.



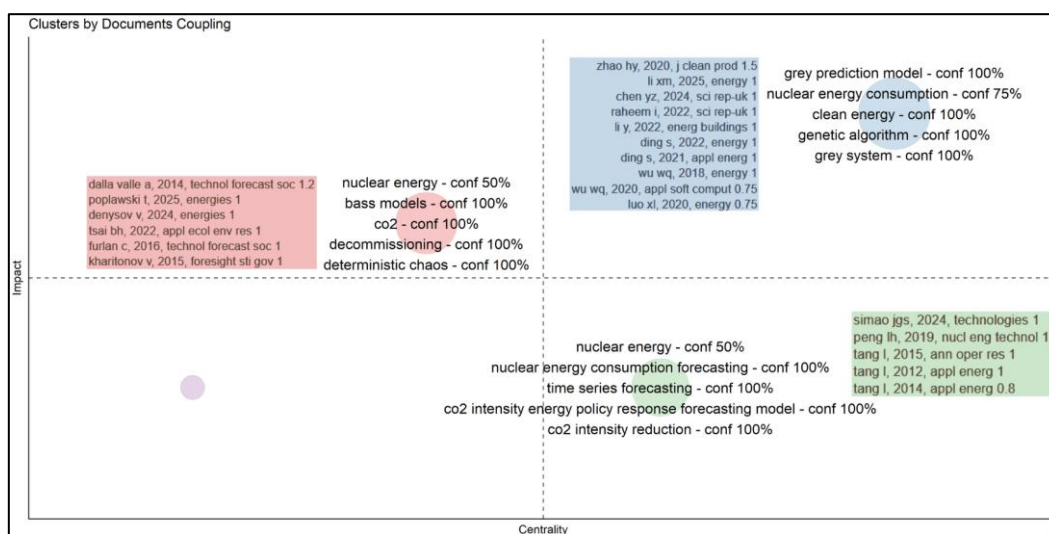
**Figure 3.** Evolutionary analysis of publication and citation trends in the nuclear energy forecasting literature (1996-2025).

**Table 1.** Most cited studies in the field of nuclear energy forecasting.

Authors	Title	Source Title	Average per Year	Citations
Tang et al. (2012)	A novel hybrid ensemble learning paradigm for nuclear energy consumption forecasting	Applied Energy	10.79	151
Wu et al. (2018)	Application of the novel fractional gray model FAGMO(1,1,k) to predict China's nuclear energy consumption	Energy	14.5	116
Ding et al. (2021)	Application of a novel structure-adaptative gray model with adjustable time power item for nuclear energy consumption forecasting	Applied Energy	20.8	104
Yue et al. (2022)	The role of carbon taxes, clean fuels, and renewable energy in promoting sustainable development: How green is nuclear energy?	Renewable Energy	24	96
Tang et al. (2015)	A novel mode-characteristic-based decomposition ensemble model for nuclear energy consumption forecasting	Annals of Operations Research	6.73	74
Wu et al. (2020)	Predicting China's energy consumption using a novel gray Riccati model	Applied Soft Computing	11.17	67
Zhao and Wu (2020)	Forecasting the non-renewable energy consumption by an adjacent accumulation gray model	Journal Of Cleaner Production	10.83	65
Tang et al. (2014)	A novel data-characteristic-driven modeling methodology for nuclear energy consumption forecasting	Applied Energy	5.33	64
Grover and Chandra (2006)	Scenario for growth of electricity in India	Energy Policy	2.75	55
Ding et al. (2022)	Forecasting nuclear energy consumption in China and America: An optimized structure-adaptative gray model	Energy	10.8	54

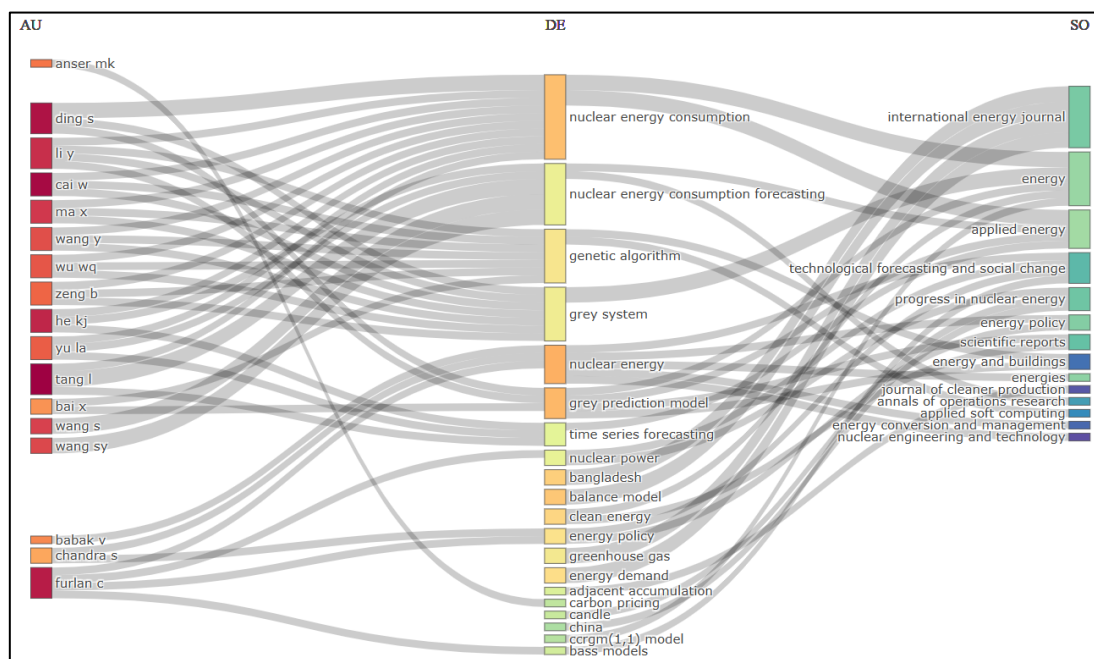
### 3.2. Network Structure and Thematic Relationships of Nuclear Energy Forecasting Research

Figure 4 shows a graph in which the horizontal axis (centrality) represents the strength of connections within the literature and the vertical axis (impact) represents the clusters' scientific impact. Each coloured box represents a cluster of studies that are either methodologically or thematically similar, and the results of the analysis reveal three main developing trends in the literature. The first cluster (the red region) comprises studies based on policy and socio-technical approaches. Comprising works such as Dalla Valle (2014) [28], Poplawski (2025) [29], Denysov (2024) [30] and Furlan (2016) [31], this group has relatively low centrality but moderate impact. Topics include nuclear energy policies, CO<sub>2</sub> reduction, decommissioning and deterministic chaos models. This cluster represents the earliest literature to address nuclear energy prediction in a socio-political context. The second cluster (blue region) constitutes the core group with the highest impact and centrality. This cluster contains highly cited works such as Zhao (2020) [32], Ding (2021–22) [25,33] and Li (2022) [34], which focus on themes such as machine learning, grey prediction, genetic algorithms and clean energy prediction. This group forms the methodological backbone of the nuclear energy prediction field, reflecting the central role of data-driven and AI-based approaches in the literature. The third cluster (green zone) consists of studies on time series modelling and energy policy. Represented by Simao (2024) [35], Peng (2019) [36] and Tang (2012–2015) [23,37,38], this cluster has high centrality and focuses on CO<sub>2</sub> intensity, energy consumption forecasts and econometric modelling. This group acts as a bridge in the transition process from classical time series analysis to hybrid modelling.



**Figure 4.** Thematic clusters according to document matching in the nuclear energy forecasting literature (1996-2025).

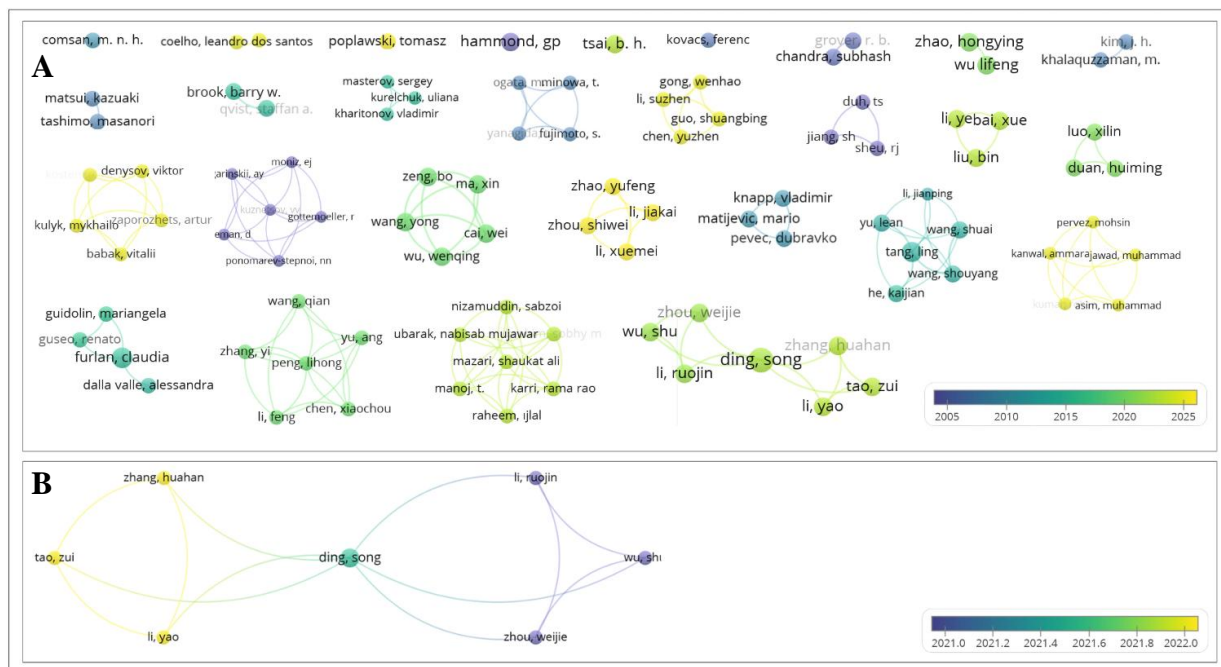
Figure 5 shows that the methodological centre of the nuclear energy forecasting field is concentrated around artificial intelligence and optimisation-based models, as illustrated by the Sankey plot. The authors with the highest level of connectivity are Ding S., Li Y., Wang Y., Wu WQ, Zeng B. and Tang L., who form the core network of literature on this topic. Their work generally relates to nuclear energy consumption, grey prediction models, genetic algorithms and machine learning-based forecasting. At the key concept level, the topics with the highest centrality are 'nuclear energy consumption forecasting', 'grey system', 'genetic algorithm', and 'time series forecasting'. This finding reveals that research focuses not only on energy consumption forecasting, but also on analytical approaches based on grey system theory, optimisation techniques and hybrid model structures. In terms of publication channels, the journals Energy, Applied Energy, Technological Forecasting and Social Change, Progress in Nuclear Energy, and Energy Policy stand out as high-impact interdisciplinary platforms combining technical modelling and optimisation with policy-based energy research. Overall, the Sankey plot shows that the nuclear energy forecasting literature is concentrated along three axes: (1) author-level Asia-centric technical research networks have formed; (2) methodological approaches involving artificial intelligence, grey systems and time series analysis dominate the literature; and (3) publication-level studies are clustered in high-impact energy and technology journals.



**Figure 5.** Relationship between top keywords (DE), authors (AU), and journals (SO) summarized by Sankey plot.

Figure 6-A illustrates the co-authorship network within the literature on nuclear energy forecasting between 1996 and 2025. Colour coding is used to represent the periods of activity of the authors. Blue represents the early period (2000–2010), green the transition period (2011–2018) and yellow the current period (2019–2025). This clearly reveals how the field evolved from a dispersed, Eurocentric structure to a dense, China-centric research network over time. During the early period (shown in blue), authors such as Furlan, C., Dalla Valle, A., and Babak, V., stood out with individual studies focusing on policy and energy economics. After 2010 (green tones), researchers such as Li Y., Wu WQ, Zeng B. and Tang L. expanded the collaborative network by popularising grey system and time series methods. Since 2019 (yellow tones), a highly interconnected core group led by Ding S., Zhou J. and Tao Z. has emerged as the scientific centre guiding the development of AI-based hybrid models.

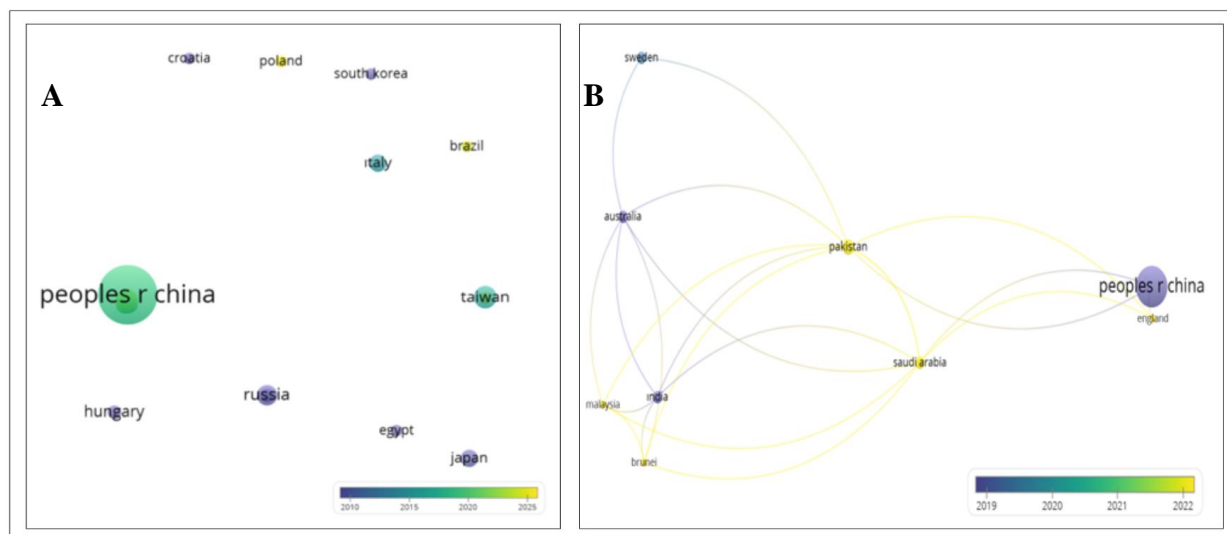
Figure 6-B shows the most connected subnetwork, highlighting the core group of seven authors centred around Ding S. This group has demonstrated high productivity and interaction since 2020. This demonstrates that the field has evolved into a mature scientific community characterised by intense collaboration in recent years.



**Figure 6.** Temporal distribution of the co-authorship network in the field of nuclear energy forecasting (**A:** General network view; **B:** Largest directly connected network).

Figure 7-A illustrates the global collaboration network in nuclear energy forecasting, clearly showing China's central position. China is a leader in terms of both publication volume and methodological diversity, with a focus on knowledge production in grey systems, AI-based optimisation, and hybrid models. In contrast, surrounding countries such as Taiwan, South Korea, Brazil and Italy have focused on fewer but higher-quality studies, particularly in the areas of energy demand and carbon-neutral scenarios. These countries have increased their visibility in the post-2020 period as the field has expanded from a technical axis to a sustainability and policy-oriented framework.

Figure 7-B shows the intensive methodological collaboration between China, Pakistan, India, Saudi Arabia, Malaysia and Australia. During the period from 2019 to 2022, these countries led the way in developing data-driven, optimisation-based and hybrid models. Furthermore, the UK's bridging role has formed a holistic research bridge between European econometric traditions and emerging AI approaches from the Asia-Pacific region.

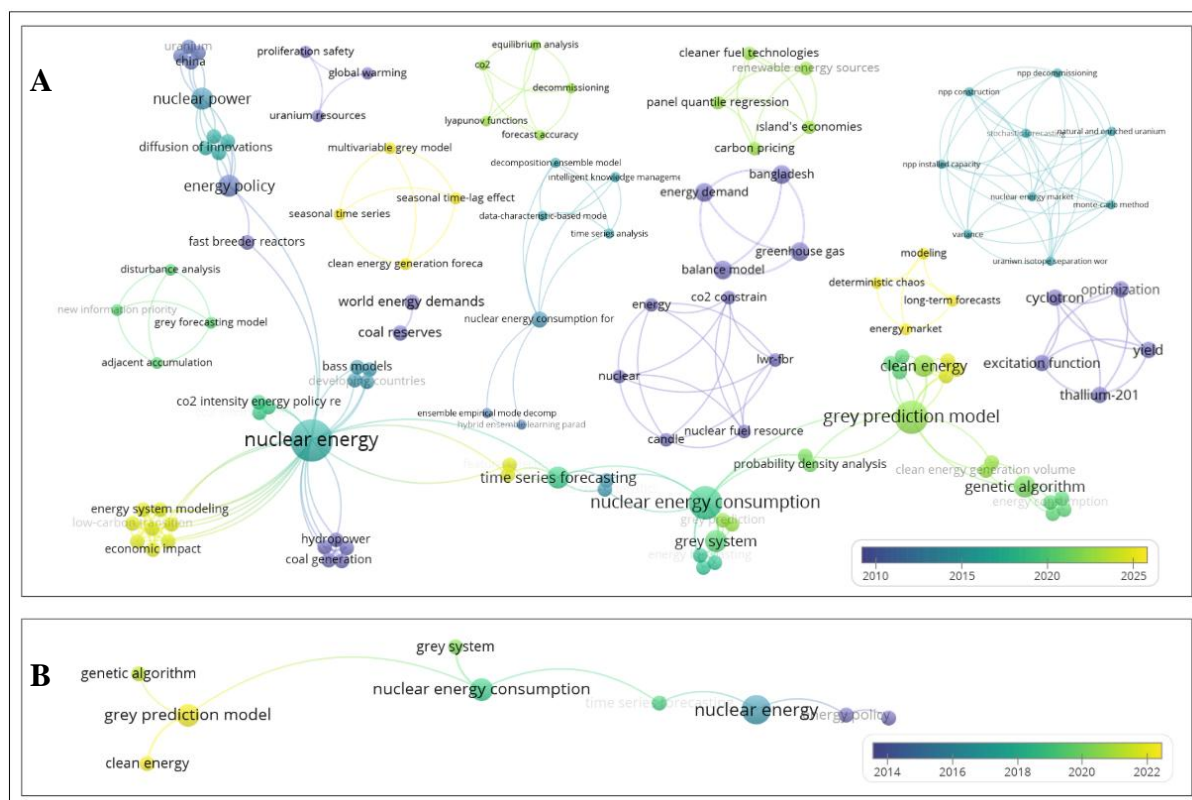


**Figure 7.** Country-level cooperation network in the field of nuclear energy forecasting (**A:** General network view; **B:** Largest directly connected network).

The keyword network visualisation offers a detailed insight into the methodological and thematic development of literature on nuclear energy forecasting from the 2010s to the 2020s. Figure 8-A shows the general network structure, demonstrating that early studies focused on concepts such as 'nuclear power', 'energy policy', 'time series forecasting', and 'coal reserves', and that econometric and policy-based forecasting models primarily shaped this period. After 2015, the network's focus shifted towards data-driven concepts such as 'grey prediction models', 'genetic algorithms',

'optimisation', 'hybrid ensembles' and 'time series forecasting'. This change represents a methodological breakthrough in nuclear energy demand and consumption research, where artificial intelligence and hybrid forecasting approaches became widespread. The yellow clusters (e.g. clean energy, carbon pricing, renewable energy sources and greenhouse gases) that emerged after 2020 demonstrate that forecasting models have evolved to encompass technical, sustainability, carbon neutrality and environmental policy components.

Figure 8-B shows the most interconnected subnetwork, summarising the core structure of this methodological evolution. The 'grey prediction model–genetic algorithm–nuclear energy consumption–clean energy' chain represents the dominant research orientation in the field today, integrating optimisation algorithms and AI-based models with energy prediction systems. This structure shows that grey system-based models, particularly those developed by Chinese research groups, have become the global standard.



**Figure 8.** Keyword networks in nuclear energy forecasting: methodological evolution and sustainability-focused thematic shifts (**A:** General network view; **B:** Largest directly linked network).

To deepen the bibliometric interpretation, keyword evolution and thematic patterns were further examined. The temporal distribution of keywords indicates that early studies were mainly associated with “nuclear power”, “energy policy”, “time series forecasting” and conventional econometric modelling. After 2015, the thematic structure shifted toward “grey prediction models”, “genetic algorithms”, “optimization” and “hybrid forecasting”. Since 2020, trend topics have increasingly included “clean energy”, “carbon neutrality”, “renewable energy integration”, “greenhouse gas reduction” and “energy security”. This transition demonstrates that nuclear energy forecasting has evolved from a narrow technical forecasting field into a broader interdisciplinary research area linking methodological innovation with sustainability-oriented policy concerns.

The thematic mapping also shows that grey system models, machine learning approaches and hybrid optimization techniques constitute the methodological core of the field. In contrast, sustainability, carbon pricing and clean energy concepts represent emerging themes that connect nuclear energy forecasting with global climate and energy-transition debates. These findings suggest that future research will likely develop around two complementary axes: improving forecasting accuracy through advanced artificial intelligence-based models and strengthening the policy relevance of forecasting outputs through scenario-based energy planning.

### **3.3. The Link Between Corporate Finance and the Sustainable Development Goals (SDGs)**

In the field of nuclear energy forecasting, the funding structure is a key factor in shaping geographical and thematic research trends. Analyses reveal that this field is primarily supported by public funds from China, focusing on themes such as clean energy, industrial innovation, and climate action. Around 27.8% of publications are funded by the National Natural Science Foundation of China (NSFC), which plays a significant role in AI-based modelling, grey system analysis and energy policy projects in particular. Other Chinese funds, such as those from Zhejiang, Sichuan and BUCT, provide regional support, while international institutions, including King Saud University (Saudi Arabia), CNPq (Brazil) and the University of Padua (Italy), contribute to research in sustainable production and energy technologies. This funding concentration underscores the robust link between Asia-Pacific-centric knowledge production and global objectives such as the energy transition, carbon neutrality, and the digital energy economy (see Table 2).

**Table 2.** Major funding organizations in the field of nuclear energy forecasting.

Funding Agency	Country	Record Count	36%	Thematic Focus
National Natural Science Foundation of China (NSFC)	China	10	27.78	AI-based modeling, energy policies, grey systems theory.
Fundamental Research Funds for the Central Universities in BUCT	China	2	5.56	Industrial energy efficiency, statistical prediction models.
King Saud University	Saudi Arabia	2	5.56	Energy demand forecasting, economic growth, and renewable integration.
National Science Fund for Distinguished Young Scholars	China	2	5.56	Hybrid optimization and AI-based prediction
Soft Science Research Program of Zhejiang Province	China	2	5.56	Energy planning, sustainable development strategies
State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University	China	2	5.56	Energy resource management, reserve estimation, geo-energy analysis.
Applied Basic Research Program of Science and Technology Commission Foundation of Sichuan Province	China	1	2.78	Optimization and system analysis in energy technologies.
Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)	Brazil	1	2.78	Econometric modeling of energy production-consumption balance.
Doctoral Research Foundation of Southwestern University of Science and Technology	China	1	2.78	Data-based modeling in emerging energy systems.
Energy Research Center Giorgio Levi Cases, University of Padua (Italy)	Italy	1	2.78	Innovative energy technologies, carbon substitution, and energy transition processes.

**Table 3.** Distribution of nuclear energy forecasting studies according to the Sustainable Development Goals.

Sustainable Development Goals	Record Count	36%	Thematic Focus
07 Affordable and Clean Energy	13	36.11	Clean energy production, carbon reduction, energy security.
09 Industry, Innovation and Infrastructure	7	19.44	Industrial innovation, infrastructure modernization
13 Climate Action	7	19.44	Combating climate change, carbon neutrality policies.
12 Responsible Consumption and Production	6	16.67	Resource efficiency, sustainable production processes.
08 Decent Work and Economic Growth	5	13.89	Energy economics, employment and growth policies
11 Sustainable Cities and Communities	2	5.56	Urban sustainability, energy infrastructure planning.
03 Good Health and Well-Being	1	2.78	Public health, energy security and environmental impact

The Sustainable Development Goals (SDGs) analysis also supports this trend in the financing structure. According to Table 3, nuclear energy forecasting literature is most strongly associated with SDG 7 (Affordable and Clean Energy) (36.1%). This indicates that studies are directly

structured around themes such as clean energy production, carbon reduction and energy security. SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action) also reflect the field's strong interaction with technology and climate policies (each 19.4%).

A strong thematic parallel is seen between the funding sources of nuclear energy forecasting research and the Sustainable Development Goals when both Table 2 and 3 are considered together. The field is oriented towards research in energy security, carbon neutrality and digital transformation policies. Against this backdrop, the China-centric funding structure and themes focusing on SDGs 7, 9 and 13 suggest that nuclear energy forecasting will remain a key area of reference in the future design of sustainable energy systems.

#### **4. FUTURE PERSPECTIVES**

The future development of nuclear energy forecasting should be evaluated through three complementary dimensions: methodological advancement, thematic maturity and policy relevance. Methodologically, the field is expected to move toward more accurate, explainable and uncertainty-aware models supported by artificial intelligence, hybrid optimisation and multidimensional data integration. In terms of thematic maturity, nuclear energy forecasting is likely to expand from conventional production and consumption estimates toward broader issues such as energy security, carbon neutrality, sustainability and geopolitical uncertainty. From a policy perspective, these forecasting outputs are increasingly important for long-term nuclear energy planning, supply security, investment timing, renewable energy integration and net-zero transition strategies.

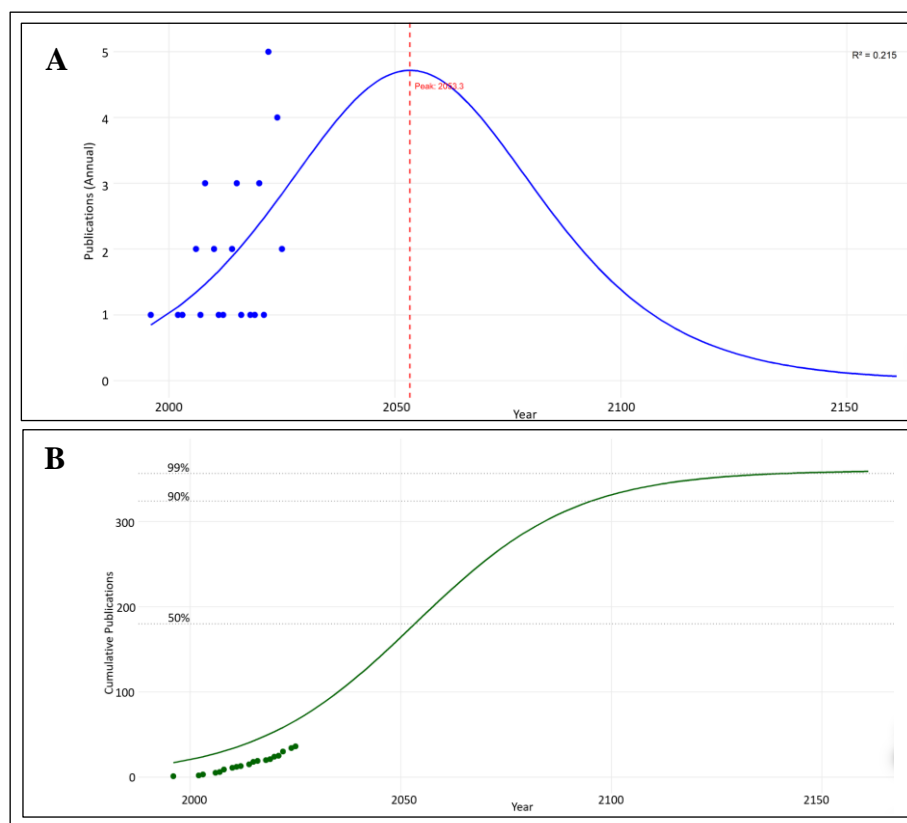
##### **4.1. Methodological and Data-Driven Evolution in Nuclear Energy Forecasting**

Analyses reveal that the types of data and methodological approaches used in nuclear energy forecasting are becoming increasingly diverse. Since 2020, models that previously focused mainly on macroeconomic indicators such as gross domestic product (GDP), population, price levels and energy consumption have undergone a significant transformation. During this period, multidimensional variables, including geopolitical risk indices, carbon intensity, renewable energy integration, uranium prices and energy security indicators, have increasingly been incorporated into modelling processes. This shift indicates that nuclear energy forecasting studies have moved beyond a purely economic perspective and have evolved into an integrated approach that also considers environmental sustainability, market uncertainty and political stability. In this context,

the comparative performance of forecasting methods has gained particular importance. While classical econometric models offer advantages in terms of interpretability, machine learning and hybrid models generally provide stronger capacity to capture nonlinear patterns and improve forecasting accuracy. Therefore, model comparisons should consider not only point-estimate accuracy but also error metrics such as RMSE, MAE and MAPE, uncertainty intervals, model stability and explainability. In the near future, innovative technologies such as big data analytics, sensor-supported energy market data and AI-powered data fusion are expected to enhance the reliability and predictive capacity of nuclear energy forecasting models. Given these developments, such models are expected to evolve into multidimensional decision-support systems that play a pivotal role in shaping energy security, net-zero targets and sustainable development policies.

#### **4.2. Quantitative Evolution and Thematic Maturity of the Field (1990 - 2160 Perspective)**

Figures 9-A and 9-B show that the volume of scientific publications in the field of nuclear energy forecasting has increased steadily over the last thirty years. According to model predictions, the publication rate will reach an average of five per year by around 2053, marking the beginning of the field's maturation phase. The trend shows that econometric model-based studies predominated in the early years, gradually giving way to artificial intelligence and hybrid approaches. The cumulative growth curve exhibits classic S-shaped logistic behaviour, predicting that the research field will reach 50% of the publication volume by 2053, 90% by 2095 and 99% by 2140. Although the model's fit coefficient ( $R^2 = 0.215$ ) appears low, this is an acceptable result given that the dataset contains only 36 publications from 1990 to 2025. The findings suggest that nuclear energy forecasting literature will evolve in parallel with global trends such as energy security, carbon neutrality and digitalisation throughout the 21st century. The rise of machine learning and optimisation-based hybrid models since 2011 reveals that the field is undergoing thematic and methodological diversification. The period between 2020 and 2040 represents a strategic phase of opportunity in which the intellectual structure of the literature will be shaped by energy policies and AI-powered economic forecasts.



**Figure 9.** Long-term development and growth estimate of nuclear energy forecasting research in the context of global energy transitions.

#### 4.3. Policy Implications for Nuclear Energy Planning and Sustainable Energy Systems

Nuclear energy forecasting has become a multidimensional decision-support area that integrates economic sustainability, environmental targets and political stability. From an economic perspective, reliable forecasts of nuclear energy production, consumption and demand can support long-term investment planning, cost optimisation, fuel-cycle management and market volatility assessment. From an environmental perspective, the integration of carbon emission indicators, renewable energy shares and sustainability parameters into forecasting models can improve the feasibility of net-zero transition pathways. At the political level, the inclusion of energy security, geopolitical risk and supply continuity indicators enables more realistic planning under uncertain global conditions.

In this context, forecasting models are not only technical tools for estimating future energy demand or production, but also strategic instruments for policy design. Energy ministries, regulatory authorities, nuclear energy agencies and national planning institutions can use advanced forecasting models to evaluate nuclear capacity expansion, determine the timing of new

investments, assess the role of nuclear power in low-carbon electricity systems and design more resilient energy portfolios. In particular, machine learning, grey system models and hybrid forecasting approaches can support scenario-based policy simulations by comparing alternative pathways for nuclear energy deployment, renewable integration and carbon-neutral energy transitions.

Therefore, future nuclear energy forecasting studies should combine methodological accuracy with policy applicability. Forecasting outputs should be transparent, explainable and supported by uncertainty analysis so that they can be effectively used in decision-making processes. Such an approach would strengthen the practical contribution of nuclear energy forecasting to energy security, sustainable energy system design and long-term low-carbon planning.

## **5. CONCLUSION**

The findings reveal that the field of nuclear energy forecasting has undergone substantial methodological and thematic transformations over the last thirty years. Initially shaped by classical econometric models, the field has gradually evolved into a multidimensional decision-support area incorporating artificial intelligence, grey system models and hybrid optimisation approaches. This transformation reflects a broader global paradigm shift associated with energy security, carbon neutrality, sustainable development goals and the increasing need for reliable long-term energy planning.

This study addresses a notable gap in the literature by examining nuclear energy forecasting not only as a technical modelling discipline, but also as a comprehensive analytical framework that supports strategic, economic and political decision-making processes. By integrating bibliometric mapping, methodological evolutionary analysis and strategic-geopolitical interpretation, the study provides a structured overview of the intellectual development and practical relevance of the field. In this respect, the findings show that nuclear energy forecasting has moved beyond a narrow prediction-oriented research area and has become an important tool for energy policy, sustainable energy system design and nuclear energy planning.

From a practical perspective, the increasing use of machine learning, grey system models and hybrid forecasting approaches indicates that nuclear energy forecasting is becoming an essential decision-support tool for long-term capacity planning, fuel-cycle management, supply security and

net-zero transition strategies. For policymakers, more accurate, transparent and explainable forecasting models can support the timing of nuclear investments, the integration of nuclear power with renewable energy systems and the evaluation of alternative decarbonisation pathways. Therefore, nuclear energy forecasting should not be considered only as a technical modelling exercise, but also as a strategic planning instrument for designing secure, sustainable and low-carbon energy systems.

Future research in this field is expected to strengthen data integration, expand the use of explainable artificial intelligence applications and support scenario-based policy simulations. In addition, future studies should combine methodological accuracy with uncertainty analysis, probabilistic forecasting and transparent model comparison in order to improve both the scientific robustness and practical applicability of forecasting outputs. Consequently, nuclear energy forecasting is expected to play a critical role in the development of sustainable, safe and low-carbon energy systems throughout the 21st century.

#### **ACKNOWLEDGEMENT**

This article is derived from Esranur Çelebi's ongoing PhD thesis, supervised by Assoc. Prof. Dr. Hüseyin Koçak, at the Graduate School of Social Sciences, Pamukkale University, Turkey.

#### **DECLARATION OF ETHICAL STANDARDS**

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

#### **CONTRIBUTION OF THE AUTHORS**

**Esranur Çelebi:** Performed the experiments, analysed the results, and wrote the manuscript.

**Hüseyin Koçak:** Analysed the results and wrote the manuscript.

#### **CONFLICT OF INTEREST**

There is no conflict of interest in this study.

#### **REFERENCES**

[1] IEA (International Energy Agency). Net Zero by 2050 (A Roadmap for the Global Energy Sector). 2021. [Online] Available from: <https://www.iea.org/reports/net-zero-by-2050>

- [2] IEA (International Energy Agency). World Energy Outlook 2024 (Executive Summary). 2024. [Online] Available from: <https://www.iea.org/reports/world-energy-outlook-2024>
- [3] IEA (International Energy Agency). Electricity Mid-Year Update 2025. 2025. [Online] Available from: <https://www.iea.org/reports/electricity-mid-year-update-2025>
- [4] NEA (Nuclear Energy Agency). The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables. 2019. [Online] Available from: [https://www.oecd-nea.org/jcms/pl\\_15000/the-costs-of-decarbonisation-system-costs-with-high-shares-of-nuclear-and-renewables?details=true](https://www.oecd-nea.org/jcms/pl_15000/the-costs-of-decarbonisation-system-costs-with-high-shares-of-nuclear-and-renewables?details=true)
- [5] NEA (Nuclear Energy Agency). NEA System Cost Analysis for Integrated Low-Carbon Electricity Systems: A Guide for Stakeholders and Policymakers. 2024. [Online] Available from: [https://www.oecd-nea.org/jcms/pl\\_91154/nea-system-cost-analysis-for-integrated-low-carbon-electricity-systems-a-guide-for-stakeholders-and-policymakers?details=true](https://www.oecd-nea.org/jcms/pl_91154/nea-system-cost-analysis-for-integrated-low-carbon-electricity-systems-a-guide-for-stakeholders-and-policymakers?details=true)
- [6] NEA (Nuclear Energy Agency). Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Approaches for their Adaptation. 2021. [Online] Available from: [https://www.oecd-nea.org/jcms/pl\\_61802/climate-change-assessment-of-the-vulnerability-of-nuclear-power-plants-and-approaches-for-their-adaptation?details=true](https://www.oecd-nea.org/jcms/pl_61802/climate-change-assessment-of-the-vulnerability-of-nuclear-power-plants-and-approaches-for-their-adaptation?details=true)
- [7] Wang, Y, Zhou Z, Betrie G, Zhang K, Yan E. Power generation-cooling water Nexus: Impacts of cooling water shortage on power system operation-a simulation case study in Illinois, US. *Applied Energy* 2025; 377: 124440.
- [8] European Commission. EU taxonomy: Complementary Climate Delegated Act to accelerate decarbonisation. 2022. [Online] Available from: [https://finance.ec.europa.eu/publications/eu-taxonomy-complementary-climate-delegated-act-accelerate-decarbonisation\\_en](https://finance.ec.europa.eu/publications/eu-taxonomy-complementary-climate-delegated-act-accelerate-decarbonisation_en)
- [9] Lyócsa Š, Todorova N. What drives the uranium sector risk? The role of attention, economic and geopolitical uncertainty. *Energy Economics* 2024; 140: 107980.
- [10] Rothwell G. Market power in uranium enrichment. *Science & Global Security* 2009; 17: 132–154.
- [11] Hong T, Fan S. Probabilistic electric load forecasting: A tutorial review. *International Journal of Forecasting* 2016; 32(3): 914-938.
- [12] Jiang H, Dong Y, Dong Y, Wang J. Probabilistic electricity price forecasting by integrating interpretable model. *Technological Forecasting and Social Change* 2025; 210: 123846.
- [13] Jia X, Dai T, Guo X. Comprehensive exploration of urban health by bibliometric analysis: 35 years and 11,299 articles. *Scientometrics* 2014; 99(3): 881-894.

- [14] Li J, Hale A. Output distributions and topic maps of safety related journals. *Safety science* 2016; 82: 236-244.
- [15] Li W, Zhao Y. Bibliometric analysis of global environmental assessment research in a 20-year period. *Environmental Impact Assessment Review* 2015; 50: 158-166.
- [16] Clarivate. Content collection and indexing process: Web of Science Core Collection. Academia & Government. 2025. [Online] Available from: <https://clarivate.com/academia-government/scientific-and-academic-research/research-discovery-and-referencing/web-of-science/web-of-science-core-collection/content-collection-and-indexing-process/>
- [17] Clarivate. Resources for Librarians and Administrators: Web of Science Clarivate LibGuides. 2025. [Online] Available from: <https://clarivate.libguides.com/librarianresources>
- [18] Hook DW, Porter SJ, Herzog C. Dimensions: building context for search and evaluation. *Frontiers in Research Metrics and Analytics* 2018; 3: 23.
- [19] National Library of Medicine. About PubMed. U.S. National Library of Medicine. 2025. [Online] Available at: <https://pubmed.ncbi.nlm.nih.gov/about/>
- [20] National Library of Medicine. Medical Subject Headings (MeSH). U.S. National Library of Medicine. 2025. [Online] Available at: <https://www.nlm.nih.gov/mesh/meshhome.html>
- [21] Van Eck N, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* 2010; 84(2): 523-538.
- [22] Ari M, Cuccurullo, C. Bibliometrix: An R-tool for comprehensive science mapping analysis. *Journal of Informetrics* 2017; 11(4): 959-975.
- [23] Tang L, Yu L, Wang S, Li J, Wang S. A novel hybrid ensemble learning paradigm for nuclear energy consumption forecasting. *Applied Energy* 2012; 93: 432-443.
- [24] Wu W, Ma X, Zeng B, Wang Y, Cai W. Application of the novel fractional grey model FAGMO (1, 1, k) to predict China's nuclear energy consumption. *Energy* 2018; 165: 223-234.
- [25] Ding S, Li R, Wu S, Zhou W. Application of a novel structure-adaptative grey model with adjustable time power item for nuclear energy consumption forecasting. *Applied Energy* 2021; 298: 117114.
- [26] Yue X, Peng MYP, Anser MK, Nassani AA, Haffar M, Zaman K. The role of carbon taxes, clean fuels, and renewable energy in promoting sustainable development: How green is nuclear energy?. *Renewable Energy* 2022; 193: 167-178.
- [27] Grover RB, Chandra S. Scenario for growth of electricity in India. *Energy Policy* 2006; 34(17): 2834-2847.

- [28] Dalla Valle A, Furlan C. Diffusion of nuclear energy in some developing countries. *Technological Forecasting and Social Change* 2014; 81: 143-153.
- [29] Popławski T. Long-Term Forecast of Peak Power Demand for Poland—Construction and Use of Simplified Forecasting Models. *Energies* 2025; 18(13): 3472.
- [30] Denysov V, Kulyk M, Babak V, Zaporozhets A, Kostenko G. Modeling nuclear-centric scenarios for Ukraine's low-carbon energy transition using diffusion and regression techniques. *Energies* 2024; 17(20): 5229.
- [31] Furlan C, Guidolin M, Guseo R. Has the Fukushima accident influenced short-term consumption in the evolution of nuclear energy? An analysis of the world and seven leading countries. *Technological Forecasting and Social Change* 2016; 107: 37-49.
- [32] Zhao H, Lifeng W. Forecasting the non-renewable energy consumption by an adjacent accumulation grey model. *Journal of Cleaner Production* 2020; 275: 124113.
- [33] Ding S, Tao Z, Zhang H, Li Y. Forecasting nuclear energy consumption in China and America: An optimized structure-adaptative grey model. *Energy* 2022; 239: 121928.
- [34] Li Y, Bai X, Liu B. Forecasting clean energy generation volume in China with a novel fractional Time-Delay polynomial discrete grey model. *Energy and Buildings* 2022; 271: 112305.
- [35] Simão JGS, Coelho LDS. Ensemble Learning for Nuclear Power Generation Forecasting Based on Deep Neural Networks and Support Vector Regression. *Technologies* 2024; 12(9): 148.
- [36] Peng L, Zhang Y, Li F, Wang Q, Chen X, Yu A. Policy implication of nuclear energy's potential for energy optimization and CO<sub>2</sub> mitigation: A case study of Fujian, China. *Nuclear Engineering and Technology* 2019; 51(4): 1154-1162.
- [37] Tang L, Yu L, He K. A novel data-characteristic-driven modeling methodology for nuclear energy consumption forecasting. *Applied Energy* 2014; 128: 1-14.
- [38] Tang L, Wang S, He K, Wang, S. A novel mode-characteristic-based decomposition ensemble model for nuclear energy consumption forecasting. *Annals of Operations Research* 2015; 234(1): 111-132.