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Methodology Article

Wind Energy Potential Assessment Using the Fuzzy Cognitive Mapping (FCM) Method

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Abstract

This study focuses on wind energy potential assessment using the Fuzzy Cognitive Mapping (FCM) method. Given the limitations of fossil resources and their negative environmental impacts, the use of renewable energy sources, especially wind energy, has become an essential necessity. This research emphasizes the assessment of wind energy potential through an analytical fuzzy model that can effectively manage the complexities of energy systems. In this study, 13 key concepts were identified, including economic growth, energy prices, return on investment, investment, demand management, and other important economic, social, and environmental factors. Data were collected through structured interviews with industry experts and the analysis of standard questionnaires, and were subsequently analyzed using the FCM model. The results of this analysis show that factors such as investment levels in wind projects, economic sustainability, and increased energy supply security have significant impacts on the development of wind energy. Additionally, the results highlight the importance of using various scenarios to predict future developments and evaluate strategic decisions in the field of renewable energy. Finally, two scenarios for wind energy development in the country were presented, specifically focusing on investment and supply security. This research not only provides comprehensive analysis of wind energy potential but also offers a conceptual framework for planning and decision-making in the development of renewable energy.

Keywords

Wind Energy Potential Assessment, Fuzzy Modeling, Multi-criteria decision-making Methods, Sustainable Development, Renewable Energy in Iran, Wind Turbines, Energy Supply Security, Scenario Planning

1. Introduction

The increasing demand for energy resources remains one of the most fundamental and pressing issues of modern society [10]. The depletion of non-renewable fossil fuels and their associated environmental challenges, such as greenhouse gas emissions and resource scarcity, have intensified the global need for alternative energy sources. Among these, renewable energy, particularly wind energy, has emerged as a sustainable and viable option. Wind energy offers numerous benefits, including being environmentally friendly, cost-effective in the long term, and widely available [4].

Wind energy is also gaining attention due to its potential to contribute significantly to global energy security and reduce reliance on fossil fuels.

According to the Global Wind Energy Council (GWEC), global wind power capacity reached 837 GW in 2022, demonstrating a consistent annual growth rate of over 10%.

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Moreover, advancements in turbine technology have reduced the cost of wind energy production, making it one of the most affordable sources of renewable energy. Governments worldwide are implementing supportive policies to achieve carbon neutrality, further accelerating the adoption of wind energy [29].

The novelty of this study lies in its integration of expert-driven Fuzzy Cognitive Mapping (FCM) to assess wind energy potential, which provides a holistic and dynamic approach to scenario analysis. Unlike traditional methods that rely solely on static models or limited datasets, this approach captures the complex interrelations among key factors, allowing for more comprehensive and adaptable decision-making. By combining qualitative insights from experts with quantitative scenario simulations, this research addresses gaps in understanding the multidimensional influences on wind energy development [19].

This study aims to assess the potential of wind energy using the Fuzzy Cognitive Mapping (FCM) method. The novelty of this approach lies in its ability to model and analyze complex, dynamic interrelations among multiple factors influencing wind energy potential. Unlike traditional static models or linear analyses, FCM integrates expert insights with mathematical simulations to capture both direct and indirect causal relationships. This enables a more comprehensive understanding of the system and allows for the exploration of diverse future scenarios, filling critical gaps in the literature on renewable energy planning. The key research questions addressed are:

1) Which dimensions have the most significant impact on the use of wind energy?
2) What are the appropriate scenarios for assessing this potential?

The findings of this study provide a framework for strategic planning and decision-making in the renewable energy sector, with a focus on identifying influential factors and simulating scenarios to optimize wind energy utilization.

2. Literature Review and Research Background

2.1. Wind Energy

Wind energy is one of the suitable and renewable energy sources recognized as a renewable energy technology. Wind turbine technology has grown successfully in many countries, including Denmark, Germany, and China [12].

Like other renewable energy sources, wind energy is widely but unevenly distributed and accessible. The unequal solar radiation across different latitudes and the Earth's uneven surface leading to temperature and pressure variations, ultimately creating wind. Additionally, the Earth's atmosphere, due to its rotation, transfers heat from tropical regions to polar areas, further generating wind.

Wind energy has a fluctuating and intermittent nature and does not blow continuously. It is considered one of the clean energy technologies because it imposes minimal impact on nature and the environment. Wind power plants do not produce any air pollutants or greenhouse gases.

Today, wind energy can be utilized for various purposes, such as generating electricity, pumping water from wells and rivers, grinding grains, threshing wheat, heating homes, and similar applications. The most common use of wind energy is through wind turbines to generate electricity, making it an important, renewable, and impactful energy source. Naturally, the energy generated from wind turbines is highly dependent on wind speed (affected by topography) and atmospheric conditions.

The growing population and the resulting increase in demand for fossil energy have led many countries toward environmentally friendly energy sources. Not only developed countries but also developing nations are keen to access this energy [12].

Renewability, lack of pollution, widespread availability across the globe, and ease of utilization have made renewable energies particularly attractive for developing countries. Consequently, renewable energy sources have been given a special role in national and international policies and programs. In this regard, our country has also initiated serious and effective efforts to develop and utilize wind energy potential [23].

Considering the recent decrease in rainfall and the announcement of drought conditions by the Ministry of Energy, as well as the fact that the infrastructure of most power plants in the country, especially in the northwest, relies on hydropower, the reduction in accessible water has become a critical issue. Furthermore, in recent decades, the growing population and increasing energy demand, coupled with concerns about the depletion of fossil fuel reserves, have highlighted the importance of renewable and new energy sources [32].

The use of wind energy has been of interest to humans for centuries; for instance, Iranians built the first windmill in the 9th century AD [15, 28]. With the emergence of the energy crisis in the 1970s, the utilization of wind energy gained greater importance than before, which led to further advancements in wind energy technologies. Today, wind energy has the fastest growth rate among other power generation technologies worldwide [16]. Easy access, affordability, and being environmentally friendly are the main reasons for this progress [13]. Germany, the United States, Denmark, India, and Spain are the most active countries in the field of using wind energy for electricity production, with over 83% of wind turbines installed in just these five countries [20]. However, the World Wind Energy Association's strategy is to ensure that by 2020, approximately 10% of the world's energy consumption will be supplied by wind energy [3].

To achieve this goal, energy researchers have focused on steps such as assessing the potential of different regions, designing wind farms, and conducting economic analyses. Since predicting the expected energy output is necessary for the economic evaluation of any wind farm Jangamshetti, developing accurate methods for assessing the wind energy potential of a region has gained increasing importance [11]. Numerous studies on wind potential assessment have been conducted worldwide in countries such as China, Brazil, Algeria, Pakistan, and others. For example, Zhou et al., in Guangzhou Province, China, identified this province as a suitable area in terms of wind resources [31].

In Iran, many areas have been studied for constructing wind farms, and several wind farms have been established. In a research project, Kavyani analyzed Iran's wind energy potential by using wind data from 1981 to 1985 from synoptic meteorological stations, taking into account the required wind speeds for electricity generation. He identified the Sistan region (Zabol station) as the best area in Iran for building wind farms. Following Sistan, the southern coasts and islands of Iran were considered the next most suitable areas for this purpose. He also identified smaller regions, such as the Manjil Valley, as suitable areas for utilizing wind energy [17].

By the end of 2010, the global installed wind power capacity was 197 gigawatts. Today, wind power worldwide has the capacity to generate 430 terawatt-hours of electricity annually, equivalent to 2.5% of the world's electricity consumption. The world's winds collectively contain approximately 2,700 terawatts of energy, about 25% of which is located within 100 meters of the Earth's surface. Even extracting just 10% of this energy would exceed the total capacity of the world's hydroelectric power [9]. Unfortunately, the use of wind energy in Iran has not seen significant development and is only utilized in limited areas such as Manjil and Binalood [5].

In Iran, with the high rate of economic growth and development activities, the annual demand for various types of energy, including electricity, has increased. Consequently, constructing new wind power plants in the country has become an undeniable necessity for economic development. Implementing such infrastructural and developmental projects can potentially impact the local environment (the environmental effects of wind power plants on the region are primarily related to the construction phase). A significant portion of these effects can be controlled, mitigated, or even minimized to zero with proper site selection [30].

2.2. Factors Affecting Wind Energy

In various scientific studies, the criteria and parameters influencing the establishment of wind power plants are generally examined in categories such as environmental, geographical, ecological, demographic, land use, hydrological, security, technical, and others. Environmental criteria include maintaining minimum distances from protected areas under the country's Environmental Protection Agency, cities and population centers, coasts, wetlands, forests, lakes, and rivers. The technical and economic criteria for the establishment of wind power plants involve selecting turbine types based on wind speeds in compliance with turbine specifications and the IEC-61400-1 standard, maintaining distances from roads (including secondary roads, highways, and expressways), railways, airports (both civilian and military), and regional power transmission lines. Geographical criteria include the maximum elevation above sea level and the maximum land slope percentage [30].

Today, the interaction between energy storage systems and the grid has attracted significant attention from researchers and network operators. Among the most innovative solutions proposed to replace fossil fuels is the use of electric vehicles and wind energy for power supply [1]. With the increasing prices of fossil fuels and the environmental issues associated with traditional energy production methods, renewable energy sources, particularly wind energy, have received considerable attention. Wind energy has experienced the fastest growth among renewable energy sources. The penetration of wind energy has reduced operational costs and emissions of harmful greenhouse gases. However, the variability of wind energy can impose adverse effects on the dynamic and static security of power systems. Integrated storage systems are studied as a solution to mitigate the impact of hourly wind energy variations on power systems.

One challenge in utilizing wind energy is the uncertainty of wind speeds and, consequently, wind power generation. This stems from the probabilistic nature of wind. Large variations and low controllability are issues that must be considered when using wind energy. Due to the stochastic characteristics of wind energy, incorporating such sources into the energy production cycle adds complexity to network planning. Additionally, because wind speeds vary in wind farms, networks where wind farm generation constitutes a significant proportion of the capacity of thermal generation units face greater uncertainties in power network operation. Conventional power plant resources face numerous challenges in compensating for these fluctuations [1].

Since the presence of wind depends on the location, spatial dependencies between wind speed and duration measurements at various points in the wind speed measurement network are expected. In other words, it is anticipated that wind speeds at closer points will be more similar than those at farther points. However, few studies have investigated spatial variations and evaluated the efficiency of interpolation methods in estimating wind speeds [5].

Based on conducted studies, the most significant factors influencing wind energy include: The lack of fuel requirements for wind turbines, reducing the consumption of fossil fuels, The free availability of wind energy, The ability to meet part of the electricity demand, The relatively lower cost of wind energy in the long term, Diversification of energy sources and movement toward a sustainable energy system, High flexibility for operation at any capacity and scale (from a few watts to several megawatts), No need for water (compared to conventional power plants such as dams), Low land requirements for installation, Job creation, Lack of environmental pollution, Decreasing production costs with the increasing size of wind turbines, Enhanced energy supply security, Reduced global warming, Stimulation of economic growth, Increased per capita income, Improved social equity, Reduction of greenhouse gas emissions [8].

2.3. The Importance of Foresight

The vast need of humanity for energy resources has always been a significant and fundamental issue. The pursuit of an inexhaustible energy source has been one of humanity's long-standing aspirations [2]. All fossil energy resources will eventually be depleted, and with the exhaustion of non-renewable fossil energy, human civilization, which is highly dependent on energy, will face disruption, leading to an increased demand for renewable energy sources [25]. On the other hand, the consumption of fossil energy resources entails specific material and environmental costs and problems [21]. The use of nuclear energy, apart from its severe environmental consequences such as nuclear waste, requires high costs and advanced technology [25]. These issues have driven humanity to constantly seek new energy sources to replace the aforementioned two; sources that are not only affordable and accessible but also produce minimal pollution during consumption.

In the near future, wind energy will become the most cost-effective energy source worldwide. The costs associated with fossil fuels, including exploration, extraction, transportation, environmental impacts, and political reactions arising from their use, cannot be accurately measured or accessed. However, it is certain that the economic indices related to large-scale use of fossil fuels are significantly higher than the current global standards. Furthermore, with the reduction of fossil fuel reserves and their natural price increases, the cost of using these resources (average short-term costs) will far exceed current standards and will no longer be economically viable. Environmental and political costs must also be added to these expenses, providing further justification for the end of the fossil fuel era [26].

In the new world, concerns about lifestyles and economic outlooks in developed and developing countries have led to significant responses to energy demand and climate tensions. Some innovations do not aim at fostering peace and friendship globally. While international organizations are concerned about environmental policies, many governments are focused on energy security and are forming energy coalitions for this purpose. For example, companies from different industries form alliances around a specific energy type and draft the future roadmap of energy based on various institutions, governments, nations, costs, and orientations [6].

The use of renewable energy not only improves economic conditions but also reduces climate issues and fosters entrepreneurship, leading to reduced oil consumption. Moreover, the affordable price of renewable energy enhances the quality of human life. Consequently, it can be stated that by 2050, fossil fuel consumption will reach a minimum level, and a significant surge in the use of renewable energy sources (solar, wind, and biomass) will occur.

The utilization of clean energy, including wind energy, is gaining attention due to its lack of environmental pollution, the provision of energy security, and its affordability. With proper economic justification, improving energy efficiency becomes easily achievable. Comprehensive efforts in the field of energy efficiency can reduce global energy demand growth by half and should be considered in foresight studies [7].

3. Materials and Methods

This research adopts an applied approach and employs a mixed-method design, combining both qualitative and quantitative methods. The methodological steps are as follows:

Literature Review and Expert Input

A thorough review of the existing literature was conducted to identify initial key concepts and parameters relevant to wind energy potential.

Structured interviews were held with five experts in renewable energy, providing insights into the interrelationships among concepts.

3.1. Key Concept Identification

Based on the expert input, 13 key concepts influencing wind energy development were identified. These include factors such as investment, energy supply security, and technological advancements.

Table 1. *List of concepts based on expert opinion.*

ID	Concepts
C_1	Economic growth
C_2	Energy prices
C_3	Return on capital
C_4	Investment
C_5	Demand management
C_6	Privatization
C_7	Government support for new energy
C_8	Increasing security of energy supply
C_9	Environmental impacts
C_{10}	Grid development
C_{11}	Weakness in innovation and use of new technologies
C_{12}	Complexity of implementation method
C_{13}	Detailed monitoring and control plan

3.2. Quantitative Data Collection and Analysis

A questionnaire was designed based on a 5-point Likert scale to gather quantitative data regarding the significance of each concept.

To analyze the collected quantitative data, various statistical methods were employed to extract meaningful insights and validate the relationships among identified concepts. The questionnaire's reliability was confirmed with a Cronbach's alpha coefficient of 0.82 underwent the following steps of analysis:

Descriptive Analysis:

Descriptive statistics, including means, standard deviations, and frequency distributions, were calculated to summarize and interpret the responses from the participants.

This analysis provided a clear understanding of the prioritization of key concepts identified during the structured interviews with experts.

Inferential Analysis:

Statistical tests, such as t-tests and ANOVA (Analysis of Variance), were conducted to assess the significance of differences between key concepts or across different respondent groups.

Correlation analysis was used to examine the strength and direction of relationships between identified concepts, aiding in the construction of the Fuzzy Cognitive Map (FCM).

Factor Validation:

Exploratory factor analysis (EFA) was applied to ensure the clustering of related items under specific concepts and to verify their alignment with the theoretical framework.

This step strengthened the reliability of the model by validating the grouping of variables within the FCM.

The results of this analysis were then visualized using bar charts and correlation matrices, highlighting the interdependencies among the variables.

The results of this analysis were then visualized using bar charts and correlation matrices, highlighting the interdependencies among the variables.

3.3. Creating Fuzzy Cognitive Maps (FCMs)

The FCM method was employed to model the dynamic relationships among the identified concepts.

The weights of the relationships were derived from expert evaluations, and the FCM model was constructed to simulate potential scenarios.

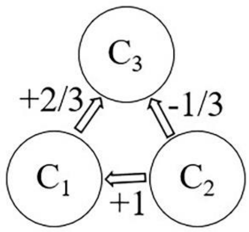
Fuzzy Cognitive Mapping (FCM) was first introduced as an enhanced and upgraded version of cognitive maps, offering a special capability to model causal and complex relationships with weighted connections [14]. FCMs have been widely used for modeling in various scientific fields, including engineering, management and business, environmental studies, medicine, and communications [24].

FCMs are graphical representations in the form of directed graphs, consisting of nodes and edges between them. The nodes represent concepts influencing the decision-making topic, while the edges depict the relationships between these concepts. In an FCM model, each concept can represent a state, variable, event, action, goal, value, or other system components. To create an FCM, it is sufficient to identify the concepts and the relationships among them concerning the main topic [24].

An FCM can be visualized using various techniques, such as:

1) Utilizing questionnaires to extract expert opinions and define variables and relationships.
2) Applying content analysis to uncover relationships in textual data.
3) Using quantitative data and conducting in-depth interviews with various experts.
4) Overall, two main approaches are used to develop FCMs:
5) Expert-based approach: Relies on expert opinions to determine relationships and weights.
6) Computational approach: Utilizes data-driven methods to develop the FCM.

In this paper, the expert-based approach is emphasized.



$$W = \begin{bmatrix} 0 & 0 & 2/3 \\ 1 & 0 & -1/3 \\ 0 & 0 & 0 \end{bmatrix}$$

Figure 1. *An example of a simple FCM.*

As shown in the following figure, in FCMs, the strength and intensity of the causal relationship between two factors Ci and Cj are represented by the edge weight (Wij). The correlation strength is expressed using linguistic variables within the range [−1, +1]: Wij=+1: Indicates a complete positive impact of concept i on concept j. Wij=−1: Indicates a complete negative impact of concept i on concept j. Wij=0: Indicates no causal relationship between i and j. The relationships among all concepts are represented in the form of an adjacency matrix, referred to as the W matrix. This matrix reflects the connections between the FCM's nodes. The W matrix remains constant over time, with concepts represented by successive rows/columns, and the matrix cells storing the weights assigned to each pair of concepts [24].

The advantages of developing an integrated methodology for constructing, developing, and ranking scenarios based on FCMs are numerous, and most of these benefits are derived from the capabilities of FCMs and the Friedman method.

The key advantages of the methodology, as highlighted in the introduction of the research process, are listed below [24]:

1) The ability to model various concepts, whether quantitative or qualitative, deterministic or uncertain, explicit or ambiguous, within a single map.
2) The capability to capture the complex knowledge of experts and extract the key concepts relevant to the modeling subject, simplifying the relationships and feedbacks among these concepts within a cognitive map.
3) Systematic collection of experiences and knowledge from both the conscious and subconscious minds of experts. Facilitating the aggregation of expert opinions into a unified map and enabling discussion and consensus among diverse experts on a specific subject.
4) No limitations on simulating diverse and varied scenarios, with high flexibility in the framework and ease of re-simulating results when variables and relationships are revised.
5) Ease in ranking scenarios and the direct use of FCM simulation results as inputs for the Friedman method.
6) Applicability of the proposed methodology for constructing, developing, and ranking scenarios based on FCMs for various topics, issues, markets, and fields.

3.4. Selection of Experts

The selection of experts is a critical step in the research process to ensure the validity and reliability of the findings. Experts were chosen based on the following criteria:

Field Expertise: Experts must have substantial knowledge and experience in renewable energy, particularly in wind energy systems and planning.

Academic and Professional Background: Individuals with advanced academic qualifications (e.g., PhD or equivalent) or significant professional roles in the energy sector were prioritized.

Years of Experience: A minimum of 10 years of experience in the field of renewable energy or related areas was required.

Diversity of Perspectives: Experts from various disciplines, including engineering, environmental science, policy-making, and economics, were included to ensure a holistic approach.

Publications and Contributions: Preference was given to individuals with published works in reputable journals or contributions to significant energy projects.

The FCM-based scenario planning process is conducted through an expert panel, and the maps are constructed by capturing and integrating the mental models of various experts. The advantage of this approach lies in its ability to identify variables present in both the conscious and subconscious minds of experts, as well as ensuring the creation of robust scenarios by merging the diverse perspectives embedded in the experts' minds [24].

3.5. Preparation of Individual Cognitive Maps

After selecting appropriate experts, structured interview sessions are conducted with each expert to extract the relevant concepts and relationships among these concepts. During these sessions, experts are asked various questions centered around the main topic, such as:

"When focusing on the main subject, what concepts or factors come to your mind?"

As a result of these questions, the concepts or nodes of the cognitive map are identified.

Subsequently, to identify the causal relationships between the concepts, further questions like "How do these concepts or factors influence each other?" are posed to the experts. Finally, experts are asked to assign fuzzy weights to the relationships between the concepts. These weights, which describe the strength or intensity of the connections between the concepts, can be determined more conveniently with the help of questionnaires.

To facilitate the estimation of weights, they can be expressed in linguistic terms or fuzzy degrees and later converted into numerical values using a predefined table [24].

Table 2. *Mapping Linguistic Terms to Numerical Values [24].*

Fuzzy Weights	Very Strong Positive Relationship	Strong Positive Relationship	Moderate Positive Relationship	Weak Positive Relationship	Zero	Weak Negative Relationship	Moderate Negative Relationship	Strong Negative Relationship	Very Strong Negative Relationship
Numerical Values	1.0	0.75	0.5	0.25	0	-0.25	-0.5	-0.75	-1.0

3.6. Aggregation of Maps

In this step of the research method, the aggregation and compression of individual FCMs (IFCMs) are performed to produce a socially agreed-upon Fuzzy Cognitive Map (SFCM) among all experts. There are various methods for merging IFCMs, or in other words, reaching consensus among experts. In this step, the IFCMs are combined to create a collective map, referred to as SFCM, which provides a holistic view of the impactful factors related to the main topic.

One of the approaches used for aggregating IFCMs and forming an SFCM is the Strategic Options Development and Analysis (SODA) approach.

SODA I provides a basis for aggregating IFCMs by performing mathematical operations on edge weights and adjacency matrices.

SODA II, on the other hand, uses group decision-making techniques, such as the Delphi method, to directly construct cognitive maps and form an SFCM by involving a group of experts.

Among the common methods in the SODA I approach, the expert credibility weighting method and the mean method are noteworthy:

In the expert credibility weighting method (Equation 1), the aggregated adjacency matrix (W_{SFCM}) is calculated by summing the product of the adjacency matrix of each IFCM and the weight or importance of the respective expert.

In the mean method (Equation 2), the aggregated adjacency matrix is derived by averaging the adjacency matrices of the individual IFCMs [24].

$$W_{SFCM} = \sum_{i=1}^{N} \propto_i . W_{IFCM_i} : \sum_{i=1}^{N} \propto_i = 1 \tag{1}$$

$$W_{SFCM} = \frac{1}{N} \sum_{i=1}^{N} W_{IFCM_i} \tag{2}$$

3.7. Reaching a Socially Agreed Fuzzy Cognitive Map

If the resulting SFCM is a complex cognitive map with numerous concepts and edges, making it difficult to comprehend and hindering the extraction of insights, efforts can be made to simplify it using graph theory techniques. Simplification can be achieved by applying the concept of compression, where subgraphs (comprising groups of interconnected concepts) are replaced with fewer categories, resulting in a simpler map.

During this process, expert consultation is utilized to merge related concepts effectively [24].

3.8. Simulation and Validation of the Fuzzy Cognitive Map

The simulation of FCMs involves iterative calculations where the state of each concept node is updated based on the influences from other connected nodes. This process continues until the system reaches a stable state or equilibrium. The steps for simulation are as follows:

Defining Input and Output Vectors:

According to the study by Salmeron, Vidal, and Mena, the final SFCM can be represented as a classic neural network consisting of input, hidden, and output layers, as shown in the figure below [22].

The nodes belonging to the input layer are activated at the initial time and have non-zero states.

The hidden layer consists of nodes that are inactive at the initial time.

Finally, the output layer includes nodes that generate future scenarios for analysis.

It is also possible for a node to simultaneously belong to both the input and output layers [24].

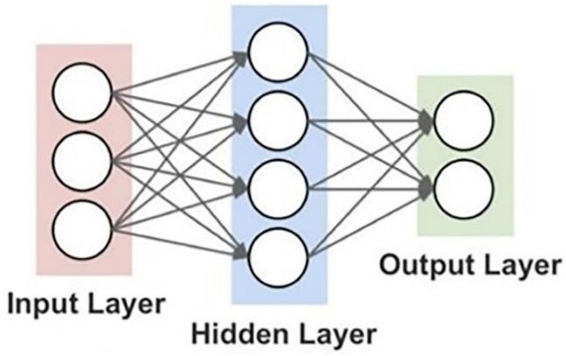


Figure 2. *Input and Output Vectors.*

Therefore, before executing the SFCM simulation, the initial state vector (ISV) must be defined by assigning values to the concepts or nodes present in the input layer. Since one of the goals of the proposed methodology is planning for various scenarios, multiple ISVs can be defined to represent all possible scenarios. Additionally, it is necessary to determine the Decision Output Concept (DOC) from among the concepts in the output layer, in such a way that it represents the overall performance of the map. In general, DOCs define the main objective and purpose of scenario planning [24].

Initialization:

Define the initial state vector representing the activation levels of each concept. For example, the input layer nodes are activated with non-zero values, while the hidden layer nodes are initialized at zero.

Weight Matrix Application:

Multiply the state vector with the adjacency matrix (weight matrix) to calculate the influence of each concept on others.

Normalization:

Apply a normalization function (e.g., sigmoid or thresholding) to ensure the state values remain within the defined range (e.g., [0,1]).

Iteration:

Repeat the process until changes in state values between iterations fall below a predefined threshold, indicating convergence.

Validation of Results

To validate the FCM model, the following methods were employed:

Expert Feedback: Experts reviewed the simulated scenarios and confirmed whether the results aligned with their domain knowledge and expectations.

Sensitivity Analysis: Adjustments were made to key parameters (e.g., weights of relationships) to test the robustness of the model and ensure stability under various conditions.

Comparison with Empirical Data: Wherever possible, the simulation results were compared with real-world data or findings from previous studies to verify their accuracy.

These steps ensure the reliability and credibility of the FCM model in analyzing and predicting the dynamics of wind energy potential.

The FCM method was employed to model the dynamic relationships among the identified concepts.

The weights of the relationships were derived from expert evaluations, and the FCM model was constructed to simulate potential scenarios.

3.9. Training and Dynamics of SFCM

FCMs are, in a way, dynamic systems with feedback loops, where changes in the ISV may affect other concepts, and the impact of the feedback loops can also influence the starting concepts (ISV) [18]. As defined in the previous step, the training of SFCM begins with the design of the initial state vector. The initial state vector of an FCM with n concepts is represented as follows, where $a_i^{(0)}$ denotes the value of concept i at time t=0:

$$A^{(0)} = (a_1{}^{(0)} a_2{}^{(0)} \dots a_n{}^{(0)}) \tag{3}$$

The state vector at time t+1 includes the new values of the nodes, which are calculated through a matrix multiplication process and iteratively. The mathematical representation of the FCM inference process is as follows [24]:

$$A^{(t)} = f(A^{(t-1)} + W_{SFCM}.A^{(t-1)}) \tag{4}$$

$$a_i^{(t)} = f(a_i^{(t-1)} + \sum_{j=1 j\neq i}^{n} a_j{}^{(t-1)}.w_{ji}) \tag{5}$$

In the above equations, $A^{(t)}$ is the vector of concept values at stage t, W_{SFCM} is the adjacency matrix after aggregation and compression, w_{ji} are the elements of this matrix, and $a_i^{(t)}$ is the value of concept C_i at stage t. Additionally, f is the activation function (or compression function or threshold function) which is applied as a threshold in the output vector after each multiplication operation. In various studies, different activation functions have been introduced. Here, since we want the result of the multiplication operation to be compressed into the range [−1,1], we use the hyperbolic tangent activation function [24].

3.10. Identification of Scenario Results

The training and inference process of SFCM ends in the previous step when the state vector $A^{(t)}$ has stabilized. At this point, the state vector represents the effect of different scenarios on the values of the SFCM nodes. In other words, the simulation process receives the required data from the defined scenarios on the input concepts, infers, and provides the output concept values as the result of the scenarios [24].

The stopping condition of this process can be in two forms. The first case occurs when the model remains in a stable pattern of node values, which is referred to as the hidden or absorbing fixed-point pattern. The other case happens when the FCM continuously produces different results or state vector values for each cycle, where the state is maintained for a specified number of iterations and is known as the limited cycle [19, 27].

4. The Model Results and Analysis

4.1. Data Analysis

In this research, to determine the validity of the research questionnaires, the opinions of several experts in the field were sought. After studying the questionnaires, they shared their feedback, and the questionnaires were revised based on their suggestions.

In this study, to assess reliability, Cronbach's alpha coefficient was used with a Likert scale questionnaire consisting of 13 five-option questions.

Descriptive and inferential statistical analyses, including ANOVA and correlation analysis, were performed to interpret the quantitative data.

Exploratory factor analysis (EFA) was used to validate the grouping of related items within the FCM framework.

By combining qualitative insights with quantitative analysis, this methodology ensures a holistic evaluation of wind energy potential and provides actionable insights for policymakers and stakeholders.

4.2. Drawing the FCM and Adjacency Matrix

Given that the concepts and variables in the wind energy development system involve economic, political, technical, environmental complexities, etc., cognitive types have been used to simplify and measure qualitative factors.

In this study, based on the opinions of experts, 13 influential concepts on wind energy development have been extracted, and their list is provided in Table 1.

Furthermore, by identifying the relationships between these concepts and their mutual influences, an individual cognitive map and an adjacency matrix (or a matrix of relationships) are represented for each expert, such that all the concepts in the cognitive map are included, and the values of the matrix, depending on the type of relationship and its influence, range between [-1,1]. The individual cognitive maps are combined using the average sum of the matrices to form a social cognitive matrix, so that we can represent the opinions of three experts in one map for the decision-making process.

Table 3. *Individual Expert 1's Relationship Matrix.*

FCM_1		**C_1** Economic growth	**C_2** Energy prices	**C_3** Return on capital	**C_4** Investment	**C_5** Demand management	**C_6** Privatization	**C_7** Government support for new energy	**C_8** Increasing security of energy supply	**C_9** Environmental impacts	**C_{10}** Grid develop ment	**C_{11}** Weakness in innovation and use of new technologies	**C_{12}** Complexity of implementation method	**C_{13}** Detailed monitoring and control plan
C_1	Economic growth	0.00	1.00	0.00	0.00	0.00	0.00	0.25	0.50	-0.75	0.00	0.00	-1.00	0.00
C_2	Energy prices	0.00	0.00	-0.25	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00
C_3	Return on capital	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_4	Investment	1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_5	Demand management	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_6	Privatization	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
C_7	Government support for new energy	1.00	0.00	0.00	0.00	0.00	-0.25	0.00	0.00	0.00	0.00	0.50	0.00	0.00
C_8	Increasing security of energy supply	1.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.50	0.00	0.00	0.00
C_9	Environmental impacts	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-0.75
C_{10}	Grid development	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00
C_{11}	Weakness in innovation and use of new	0.00	0.00	0.00	0.00	0.00	0.00	0.25	1.00	0.00	0.00	0.00	0.00	0.00

FCM$_1$		**C$_1$** Economic growth	**C$_2$** Energy prices	**C$_3$** Return on capital	**C$_4$** Investment	**C$_5$** Demand management	**C$_6$** Privatization	**C$_7$** Government support for new energy	**C$_8$** Increasing security of energy supply	**C$_9$** Environmental impacts	**C$_{10}$** Grid development	**C$_{11}$** Weakness in innovation and use of new technologies	**C$_{12}$** Complexity of implementation method	**C$_{13}$** Detailed monitoring and control plan
	technologies													
C$_{12}$	Complexity of implementation method	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
C$_{13}$	Detailed monitoring and control plan	0.75	0.50	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

$$FCM_1 = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0.25 & 0.5 & -0.75 & 0 & 0 & -1 & 0 \\ 0 & 0 & -0.25 & 0 & 0 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & -0.25 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 \\ 1 & 0.75 & 0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -0.75 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0.75 & 0.5 & 0 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

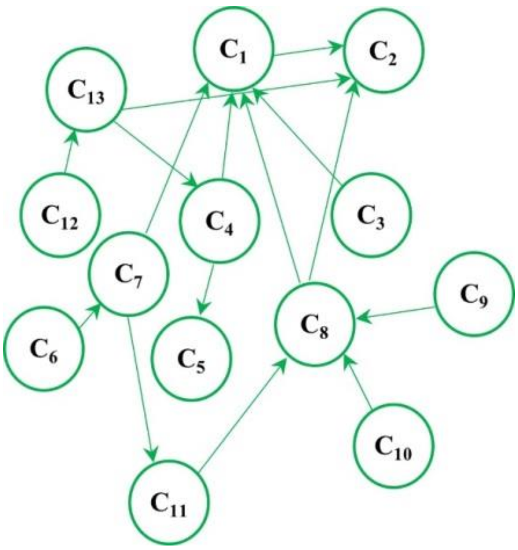


Figure 3. *Expert 1's Cognitive Map.*

Table 4. *Individual Expert 2's Relationship Matrix.*

FCM$_2$		**C$_1$** Economic growth	**C$_2$** Energy prices	**C$_3$** Return on capital	**C$_4$** Investment	**C$_5$** Demand management	**C$_6$** Privatization	**C$_7$** Government support for new energy	**C$_8$** Increasing security of energy supply	**C$_9$** Environmental impacts	**C$_{10}$** Grid development	**C$_{11}$** Weakness in innovation and use of new technologies	**C$_{12}$** Complexity of implementation method	**C$_{13}$** Detailed monitoring and control plan
C$_1$	Economic growth	0.00	0.75	0.25	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.25
C$_2$	Energy prices	0.25	0.00	0.00	0.00	-0.25	0.00	0.00	0.50	-0.50	0.00	0.00	0.00	0.00
C$_3$	Return on capital	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.25	0.00
C$_4$	Investment	0.75	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C$_5$	Demand management	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
C$_6$	Privatization	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00
C$_7$	Government support for new energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.00	0.00	0.75	0.00	0.00
C$_8$	Increasing security of energy supply	0.50	1.00	-0.50	0.00	0.00	0.00	0.25	0.00	0.00	0.50	0.25	0.00	0.00
C$_9$	Environmental impacts	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.00	-1.00	0.00
C$_{10}$	Grid development	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
C$_{11}$	Weakness in innovation and use of new technologies	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.75	0.00	-1.00	0.00	0.00	0.00
C$_{12}$	Complexity of implementation method	0.00	0.00	0.00	-0.75	0.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75
C$_{13}$	Detailed monitoring and control plan	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.00

$$FCM_2 = \begin{bmatrix} 0 & 0.75 & 0.25 & 0 & 0 & 0 & 0 & 0.25 & 0 & 0 & 0 & 0 & 0.25 \\ 0.25 & 0 & 0 & 0 & -0.25 & 0 & 0 & 0.5 & -0.5 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.25 & 0 \\ 0.75 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.5 & 0 & 0 & 0 & 0 & 0.75 & 0 & 0 & 0.75 & 0 & 0 \\ 0.5 & 1 & 0 & 0 & 0 & 0 & 0.25 & 0 & 0 & 0.5 & 0.25 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.75 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.75 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0.75 \\ 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 0 \end{bmatrix}$$

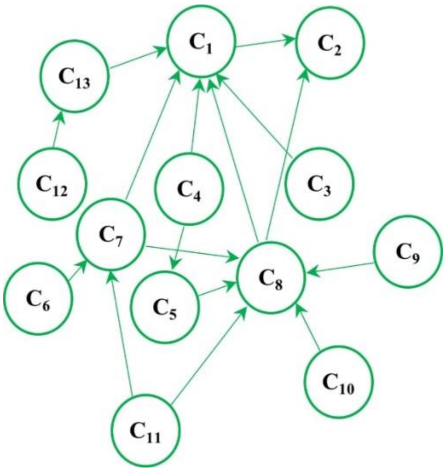


Figure 4. *Expert 2's Cognitive Map.*

Table 5. *Individual Expert 3's Relationship Matrix.*

FCM$_3$		**C$_1$** Economic growth	**C$_2$** Energy prices	**C$_3$** Return on capital	**C$_4$** Investment	**C$_5$** Demand management	**C$_6$** Privatization	**C$_7$** Government support for new energy	**C$_8$** Increasing security of energy supply	**C$_9$** Environmental impacts	**C$_{10}$** Grid development	**C$_{11}$** Weakness in innovation and use of new technologies	**C$_{12}$** Complexity of implementation method	**C$_{13}$** Detailed monitoring and control plan
C$_1$	Economic growth	0.00	1.00	0.50	1.00	1.00	0.00	0.25	0.75	0.00	1.00	0.00	0.00	0.00
C$_2$	Energy prices	0.50	0.00	0.00	1.00	0.00	-1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
C$_3$	Return on capital	0.75	0.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00
C$_4$	Investment	0.50	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	-0.25	0.00	0.00
C$_5$	Demand manage-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.00	0.00	0.00	0.00	0.00

FCM$_3$		**C_1** Economic growth	C_2 **Energy prices**	**C_3** **Return on capital**	**C_4** **Investment**	**C_5** **Demand management**	**C_6** **Privatization**	**C_7** **Government support for new energy**	**C_8** **Increasing security of energy supply**	**C_9** **Environmental impacts**	**C_{10}** **Grid development**	**C_{11}** **Weakness in innovation and use of new technologies**	**C_{12}** **Complexity of implementation method**	**C_{13}** **Detailed monitoring and control plan**
	ment													
C_6	Privatization	0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	-0.50	0.00
C_7	Government support for new energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
C_8	Increasing security of energy supply	1.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.75	0.00	0.00	0.00
C_9	Environmental impacts	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
C_{10}	Grid development	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.25	0.00	0.00	0.00	0.00
C_{11}	Weakness in innovation and use of new technologies	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.50	0.00	0.00	0.00	0.50	0.00
C_{12}	Complexity of implementation method	0.00	0.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	1.00
C_{13}	Detailed monitoring and control plan	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

$$FCM_3 = \begin{vmatrix} 0 & 1 & 0.5 & 1 & 1 & 0 & 0.25 & 0.75 & 0 & 1 & 0 & 0 & 0 \\ 0.5 & 0 & 0 & 1 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0.75 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -0.25 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.75 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0.25 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.75 & 0.5 & 0 & 0 & 0 & 0.5 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

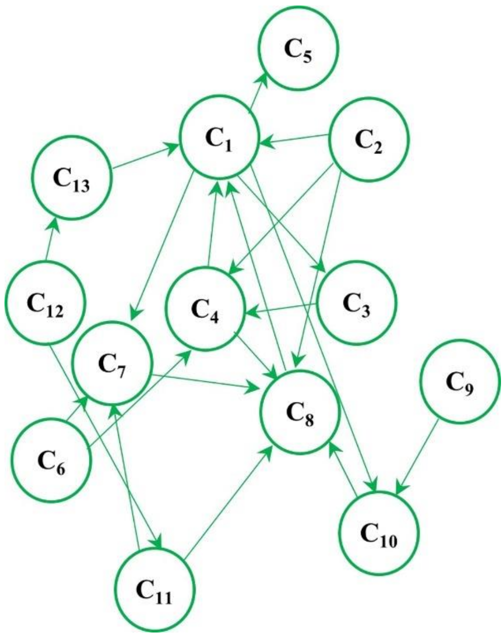


Figure 5. Expert 3's Cognitive Map.

Table 6. Social Cognitive Matrix.

SFCM		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
		Economic growth	Energy prices	Return on capital	Investment	Demand management	Privatization	Government support for new energy	Increasing security of energy supply	Environmental impacts	Grid development	Weakness in innovation and use of new technologies	Complexity of implementation method	Detailed monitoring and control plan
C_1	Economic growth	0.00	0.92	0.25	0.33	0.33	0.00	0.17	0.50	-0.25	0.33	0.00	-0.33	0.08
C_2	Energy prices	0.25	0.00	-0.08	0.33	-0.08	-0.33	0.00	0.75	-0.17	0.00	0.00	0.00	0.00
C_3	Return on capital	0.75	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.08	-0.33

SFCM		C_1 Economic growth	C_2 Energy prices	C_3 Return on capital	C_4 Investment	C_5 Demand management	C_6 Privatization	C_7 Government support for new energy	C_8 Increasing security of energy supply	C_9 Environmental impacts	C_{10} Grid development	C_{11} Weakness in innovation and use of new technologies	C_{12} Complexity of implementation method	C_{13} Detailed monitoring and control plan
C_4	Investment	0.75	0.00	0.00	0.00	0.50	0.00	0.00	0.33	0.00	0.00	-0.08	0.00	0.00
C_5	Demand management	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.33	-0.33	0.00	0.00	0.00	0.00
C_6	Privatization	0.00	0.00	0.00	0.33	0.00	0.00	0.75	0.00	0.00	0.00	0.00	-0.17	0.00
C_7	Government support for new energy	0.33	0.00	0.00	0.00	0.00	-0.08	0.00	0.58	0.00	0.00	0.42	0.00	0.00
C_8	Increasing security of energy supply	0.83	0.58	-0.17	0.00	0.00	0.00	0.25	0.00	0.08	0.58	0.08	0.00	0.00
C_9	Environmental impacts	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.33	0.00	-0.33	-0.25
C_{10}	Grid development	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.08	0.00	0.00	0.00	0.00
C_{11}	Weakness in innovation and use of new technologies	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.75	0.00	-0.33	0.00	0.17	0.00
C_{12}	Complexity of implementation method	0.00	0.00	-0.33	-0.25	0.00	-0.33	0.00	0.00	0.00	0.00	0.33	0.00	0.92
C_{13}	Detailed monitoring and control plan	0.75	0.17	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00

$$SFCM = \begin{vmatrix} 0 & 0.92 & 0.25 & 0.33 & 0.33 & 0 & 0.17 & 0.5 & -0.25 & 0.33 & 0 & -0.33 & 0.08 \\ 0.25 & 0 & -0.08 & 0.33 & -0.08 & -0.33 & 0 & 0.75 & -0.17 & 0 & 0 & 0 & 0 \\ 0.75 & 0 & 0 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.08 & -0.33 \\ 0.75 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.33 & 0 & 0 & -0.08 & 0 & 0 \\ 0 & 0 & 0 & 0.08 & 0 & 0 & 0 & 0.33 & -0.33 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.33 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & -0.17 & 0 \\ 0.33 & 0 & 0 & 0 & 0 & -0.08 & 0 & 0.58 & 0 & 0 & 0.42 & 0 & 0 \\ 0.83 & 0.58 & -0.17 & 0 & 0 & 0 & 0.25 & 0 & 0.08 & 0.58 & 0.08 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0.33 & 0 & -0.33 & -0.25 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.67 & 0.08 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.67 & 0.75 & 0 & -0.33 & 0 & 0.17 & 0 \\ 0 & 0 & -0.33 & -0.25 & 0 & -0.33 & 0 & 0 & 0 & 0 & 0.33 & 0 & 0.92 \\ 0.75 & 0.17 & 0 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0 \end{vmatrix}$$

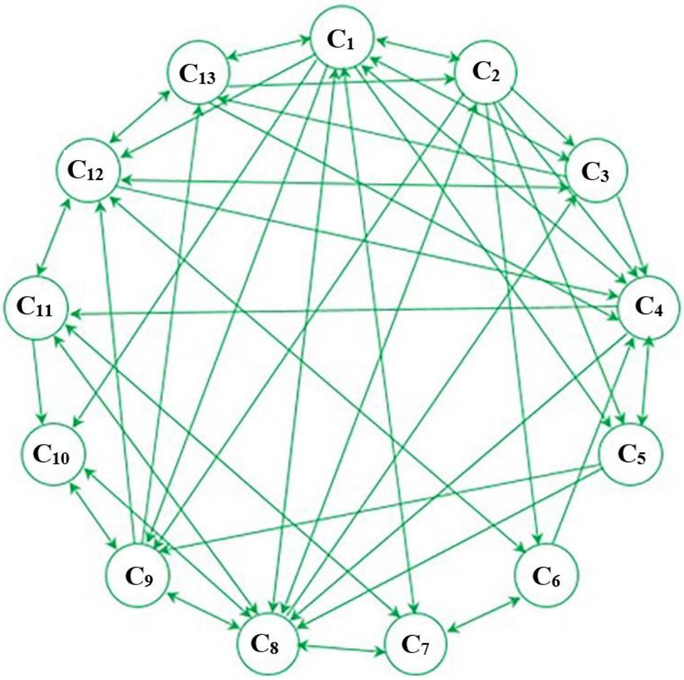


Figure 6. *Social Cognitive Map.*

4.3. Scenario Simulation

Scenario simulation was conducted using the Fuzzy Cognitive Mapping (FCM) method, which facilitates modeling the dynamic relationships among concepts and predicting the impact of various scenarios. The simulation involved the following steps:

Scenario Definition:

Two primary scenarios were developed based on expert input and literature review:

Scenario A: Focused on increased investment in wind energy infrastructure.

Scenario B: Centered on enhancing energy supply security.

These scenarios were designed by varying the weights of key concepts in the social matrix of the FCM.

Simulations were conducted using software tools such as MATLAB, with the social matrix of the FCM providing the basis for evaluating the impacts of each scenario.

Scenario A: Focused on increased investment in wind energy infrastructure.

In Scenario A, energy price (C_2), return on investment (C_3), investment (C_4), privatization (C_6), and grid development (C_{10}) are considered as input variables, and in the input vector, these concepts are assigned the value of one, while the rest of the concepts are assigned a value of zero.

The input vector for Scenario A is as follows:

$$A = |0 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0|$$

And by multiplying the vector with the social adjacency matrix, the vector A' is obtained, and this compression continues until the last two vectors become identical, at which point the simulation stops.

$$A' = |0 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0| \times$$

$$\begin{vmatrix}
0 & 0.92 & 0.25 & 0.33 & 0.33 & 0 & 0.17 & 0.5 & -0.25 & 0.33 & 0 & -0.33 & 0.08 \\
0.25 & 0 & -0.08 & 0.33 & -0.08 & -0.33 & 0 & 0.75 & -0.17 & 0 & 0 & 0 & 0 \\
0.75 & 0 & 0 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.08 & -0.33 \\
0.75 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.33 & 0 & 0 & -0.08 & 0 & 0 \\
0 & 0 & 0 & 0.08 & 0 & 0 & 0 & 0.33 & -0.33 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.33 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & -0.17 & 0 \\
0.33 & 0 & 0 & 0 & 0 & -0.08 & 0 & 0.58 & 0 & 0 & 0.42 & 0 & 0 \\
0.83 & 0.58 & -0.17 & 0 & 0 & 0 & 0.25 & 0 & 0.08 & 0.58 & 0.08 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0.33 & 0 & -0.33 & -0.25 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.67 & 0.08 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.67 & 0.75 & 0 & -0.33 & 0 & 0.17 & 0 \\
0 & 0 & -0.33 & -0.25 & 0 & -0.33 & 0 & 0 & 0 & 0 & 0.33 & 0 & 0.92 \\
0.75 & 0.17 & 0 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0
\end{vmatrix}$$

$$A' = |1.75 \quad 0 \quad -0.08 \quad 0.91 \quad -0.42 \quad -0.33 \quad 0.75 \quad 0.75 \quad -0.07 \quad 0 \quad -0.08 \quad -0.25 \quad -0.33| \xrightarrow{f(x)=\begin{cases}0, & x\le 0\\ 1, & x>0\end{cases}}$$

$$A' = |1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0|$$

$$A'' = |1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1|$$

$$A''' = |1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1|$$

Therefore, in the scenario, in the final output vector, the following concepts are active: economic growth (C_1), energy price (C_2), investment (C_4), demand management (C_5), government support for renewable energy (C_7), increased energy supply security (C_8), grid development (C_{10}), weakness in innovation and use of new technologies (C_{11}), and a precise monitoring and control program (C_{13}).

Input nodes or driving concepts

Changes	**C_2** Energy prices	**C_3** Return on capital	**C_4** Investment	**C_6** Privatization	**C_{10}** Grid development
Change 1	Rising energy prices	Increase return on investment	Increased investment	Increased privatization	Increasing local potential
Change 2	No change in energy prices	Stability in return on investment	No change in investment	No change in privatization	No change in local potential
Change 3	Reducing energy prices	Reduced return on investment	Investment reduction	Reducing privatization	Reducing local potential

Figure 7. *Visualization of the result of the scenario A.*

Scenario B: Centered on enhancing energy supply security.

In scenario B, energy price (C_2), demand management (C_5), privatization (C_6), increased energy supply security (C_7), and a detailed monitoring and control program (C_{13}) are considered as input variables, and these concepts are assigned the value of one in the input vector, while the remaining concepts are considered to be zero.

The input vector for scenario B is as follows:

$$B = |0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1|$$

And by multiplying the vector by the social adjacency matrix, the vector B' is obtained. This compression continues until the last two vectors become identical, at which point the simulation stops.

$$B' =$$

$$|0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1| \times$$

$$\begin{vmatrix}
0 & 0.92 & 0.25 & 0.33 & 0.33 & 0 & 0.17 & 0.5 & -0.25 & 0.33 & 0 & -0.33 & 0.08 \\
0.25 & 0 & -0.08 & 0.33 & -0.08 & -0.33 & 0 & 0.75 & -0.17 & 0 & 0 & 0 & 0 \\
0.75 & 0 & 0 & 0.25 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.08 & -0.33 \\
0.75 & 0 & 0 & 0 & 0.5 & 0 & 0 & 0.33 & 0 & 0 & -0.08 & 0 & 0 \\
0 & 0 & 0 & 0.08 & 0 & 0 & 0 & 0.33 & -0.33 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.33 & 0 & 0 & 0.75 & 0 & 0 & 0 & 0 & -0.17 & 0 \\
0.33 & 0 & 0 & 0 & 0 & -0.08 & 0 & 0.58 & 0 & 0 & 0.42 & 0 & 0 \\
0.83 & 0.58 & -0.17 & 0 & 0 & 0 & 0.25 & 0 & 0.08 & 0.58 & 0.08 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.5 & 0 & 0.33 & 0 & -0.33 & -0.25 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.67 & 0.08 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.67 & 0.75 & 0 & -0.33 & 0 & 0.17 & 0 \\
0 & 0 & -0.33 & -0.25 & 0 & -0.33 & 0 & 0 & 0 & 0 & 0.33 & 0 & 0.92 \\
0.75 & 0.17 & 0 & 0.08 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.08 & 0
\end{vmatrix}$$

$$B' = |1.33 \quad 0 \quad 0.17 \quad 0.82 \quad -0.08 \quad -0.41 \quad 0 \quad 1.68 \quad -0.5 \quad 0 \quad 0.42 \quad 0.08 \quad -0.33| \xrightarrow{f(x)=\begin{cases}0, & x\le 0\\ 1, & x>0\end{cases}}$$

$$B' = |1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1 \quad 0|$$

$$B'' = |1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1|$$

$$B''' = |1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1|$$

Therefore, in the final output vector of the scenario, the following concepts are active: economic growth (C_1), energy price (C_2), investment (C_4), demand management (C_5), government support for renewable energy (C_7), increased energy supply security (C_8), grid development (C_{10}), weakness in innovation and use of new technologies (C_{11}), and a detailed monitoring and control program (C_{13}).

Input nodes or driving concepts

Changes	**C_2** Energy prices	**C_5** Demand management	**C_6** Privatization	**C_7** Government support for new energy	**C_{13}** Detailed monitoring and control plan
Change 1	Rising energy prices	Increased demand	Increased privatization	Increasing government support for new energy	Increasing meteorological potential
Change 2	No change in energy prices	Demand stability	No change in privatization	Lack of government support for new energy	Stability of meteorological potential
Change 3	Reducing energy prices	Demand reduction	Reducing privatization	Reducing government support for renewable energy	Reducing meteorological potential

Figure 8. *Visualization of the result of the scenario B.*

Impact Assessment:

The simulation results showed how changes in critical factors (e.g., investment, energy supply security) influenced the development of wind energy.

For Scenario A, increased investment significantly amplified the positive feedback loops within the system, leading to accelerated growth in wind energy utilization.

For Scenario B, enhancing energy supply security reduced dependency on fossil fuels and improved system stability.

5. Discussion and Conclusion

Descriptive and inferential analysis of the research results

The results of the simulation showed how changes in critical factors (such as investment and energy supply security) impacted the development of wind energy. For scenario A, an increase in investment significantly strengthened positive feedback loops within the system, leading to rapid growth in wind energy usage. For scenario B, improving energy supply security reduced dependency on fossil fuels and enhanced system stability.

The results of the scenario simulation are presented in Figures 6 and 7.

Since the goal of this study was to assess the potential of wind energy in the context of the country's conditions, it focused on identifying key concepts influencing this area. Based on the results, scenarios for the development and use of wind energy were formulated, and the research questions were addressed. To gather data, a questionnaire was distributed among relevant experts, and its validity and reliability were deemed satisfactory.

According to the results obtained from the FCM method, 13 concepts were identified: economic growth, energy price, return on investment, investment, demand management, privatization, government support for renewable energy, wind energy development, environmental impacts, network development, weakness in innovation and the use of new technologies, complexity of the implementation method, and a detailed monitoring and control program. By defining the relationships among these concepts and their impact on each other, a cognitive map and an adjacency matrix were created for each expert. Thus, based on the resulting social cognitive matrix, the experts' opinions were represented in a map for the decision-making process.

The findings of this study revealed that investment and energy supply security factors have the greatest impact on wind energy development. Scenario analysis indicates that increased investment in wind energy could improve economic growth, reduce dependence on fossil fuels, and enhance energy security. Furthermore, government support and network development also play significant roles in harnessing the potential of wind energy. This study provides a comprehensive framework for identifying and prioritizing factors affecting wind energy development. It also offers a strong foundation for planning and decision-making in the renewable energy sector by combining quantitative analysis and scenario simulation. Future research could expand the model by integrating additional factors such as technological advancements and social acceptance.

Enhanced Analysis of Results

The results of this study indicate that factors such as investment, energy supply security, and technological advancement play pivotal roles in determining the potential of wind energy development. These findings align with previous studies that emphasize the importance of financial incentives and infrastructure in accelerating renewable energy adoption Kosko and Salmeron et al. For example, the positive correlation observed between investment and energy supply security in this study echoes the conclusions drawn by Salmeron et al., who highlighted the central role of financial backing in ensuring grid reliability and energy independence.

Moreover, this study introduces a unique application of Fuzzy Cognitive Mapping (FCM) to model the complex interrelations among key factors. Unlike traditional linear models, the FCM approach allows for a dynamic analysis of both direct and indirect causal relationships, providing richer insights into the systemic impact of each factor. For instance, the simulation results demonstrated how public awareness indirectly influences grid reliability by fostering policy support, a finding supported by Shafia and Rahimi Moghaddam.

Comparative Insights with Existing Literature

While prior research has explored various aspects of wind energy potential, few studies have integrated expert-driven FCMs to simulate and evaluate diverse future scenarios. The two scenarios presented in this study—focusing on investment growth and energy supply security—build on the work of Kosko by extending the FCM framework to incorporate real-world policy and technological variables. This approach not only validates the robustness of FCM as a decision-making tool but also provides actionable insights for policymakers.

For instance, Scenario A highlights how targeted investments can amplify technological advancements, a conclusion that resonates with the findings of International Renewable Energy Agency (IRENA), who demonstrated the compounding effects of technological progress on reducing costs in renewable energy projects. Similarly, Scenario B underscores the role of enhanced energy supply security in stabilizing grid operations and fostering energy independence, aligning with global policy recommendations outlined by the International Renewable Energy Agency (IRENA).

Research Limitations

This study faced several limitations. First, the limited number of experts interviewed due to difficulties in accessing specialists in the renewable energy sector. Second, the subjective nature of the FCM method, which may affect the interpretation of results. Third, the focus on a specific geographical region, which limits the generalization of the results to other regions. These factors may have impacted the accuracy of the findings.

Policy Implications and Research suggestions and recommendations

1) Increase government and private sector investment in wind energy projects;
2) Prioritize regulatory frameworks to ensure energy supply security while integrating renewable sources;
3) Focus on regions with high wind potential and implement targeted policies to support infrastructure development;
4) Develop hybrid energy systems to mitigate the variability of wind energy and enhance grid reliability;
5) Investigating the economic and social impacts of wind energy development in different regions of the country: This would involve a comprehensive analysis of how wind energy affects local economies, job creation, and community welfare across various regions;
6) Using advanced data analysis models, such as multi-criteria decision-making systems: These models can help better evaluate complex scenarios by considering multiple factors and priorities, offering a more nuanced

and robust approach to decision-making;

7) Evaluating wind energy potential at the regional scale with more accurate geographic and climatic data: This would improve the accuracy of assessments by using high-quality, region-specific data to identify the most suitable areas for wind energy development;
8) Expanding studies to identify the impact of government policies and regulations on renewable energy development: Understanding how various policies, subsidies, or regulations influence the growth of renewable energy technologies would provide insights for shaping more effective strategies;
9) Proposing the development of smart infrastructure for optimal management and utilization of wind energy: This would include advanced grid systems, energy storage solutions, and smart technologies that allow for efficient energy production, distribution, and consumption, ensuring the integration of wind energy into the broader energy system;

The findings of this study have significant implications for renewable energy policy and planning. Policymakers are encouraged to:

1) Prioritize investments in wind energy infrastructure to maximize technological advancements and cost efficiency.
2) Implement awareness campaigns to increase public support for renewable energy policies.
3) Strengthen international collaboration to share best practices and technologies in grid management and energy storage.

Future research could extend this study by incorporating additional variables such as geopolitical factors and consumer behavior or technological advancements and societal acceptance into the FCM framework. Moreover, longitudinal studies could validate the dynamic effects observed in this research, offering deeper insights into the temporal evolution of wind energy systems.

By bridging gaps in existing literature and providing a comprehensive, multi-dimensional analysis, this study contributes to the growing body of knowledge on renewable energy and underscores the utility of FCM in addressing complex, interconnected challenges in energy planning.

Abbreviations

FCM	Fuzzy Cognitive Mapping
GWEC	Global Wind Energy Council
ANOVA	Analysis of Variance
EFA	Exploratory Factor Analysis
IFCM	Individual Fuzzy Cognitive Mapping
SFCM	Socially Agreed-upon Fuzzy Cognitive Mapping
SODA	Strategic Options Development and Analysis
ISV	Initial State Vector
DOC	Decision Output Concept
IRENA	International Renewable Energy Agency

Conflicts of Interest

The authors declare no conflicts of interest.

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