# Identification of wind energy deployment determinants: Fuzzy cognitive map-based method

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***Abstract***

**Wind energy is undoubtedly an essential generation source required to achieve a transformative renewable energy supply portfolio. However, long-term sustainable wind energy deployment faces various challenges due to various complex interconnected impediment factors. These inherent endogenous and exogenous uncertainties preclude obtaining an accurate future trend, which complicates the design of a good policy. This study seeks to critically identify all the involved parameters that contribute to the future of wind energy in Iran. In doing so, the research employs Fuzzy Cognitive Maps to analyse the relationship and role of each determined element within the system. The research outcome revealed 26 influential factors shaping the dynamics of the system in six main categories (PESTEL). The findings demonstrated that Iran's wind sector is predominated by economic and political drivers with strong interconnections. Five key concepts, including two economic, one legal, and two political, were ascertained that contribute to the system's stability.**

***Keywords: Wind Energy; Fuzzy Cognitive Map; Renewable Energies***

## I. INTRODUCTION

The roller-coaster of Iran's international policy is rolling fast fuelled by nuclear matters with big world powers participation. The resulting governmental changes over the past years have been dramatic in the country's energy sector. Privatization and economic reformations have postponed at the expense of these disruptions. The reliance on oil and gas exports is at 60% of total revenue and 80% of export earnings [1] Sufficient sources of renewable energies (REs) relying financially on fossil fuel exports have been more defenceless yet less prioritized sectors. In recent years, wind energy has consistently been one of RE's fastest-growing sources. Onshore and offshore wind energy globally account for more than 19.1% (or 622,408 MW) of the total electricity generation by REs, which is just a piece of the total capacity (1,263,914 GWH) [2]. Despite the significant production capacity (i.e., 39,420 GWH) in Iranian wind farms, the sector is vulnerable and overly exposed to the mentioned factors. Under the current inconsistent positions, the industry ability to achieve intentions set has remained an open question. To address this gap, the FCM approach investigates the characteristics, communications, and influences of concepts. The FCM-based framework is built in a participatory workshop and is bolstered throughout a survey. This study seeks to promote wind energy in Iran and enrich the burgeoning literature by using FCM in the RE sector to identify the most critical factors influencing the expansion of this industry and design strong strategic decisions.

## II. Fuzzy Cognitive Mapping Procedure

FCM is a mapping and qualitative simulation method used to visualise dynamic multidimensional models by providing causation and modelling input values to simulate variations of a complicated system. For the researchers who use this method, the key considerations are the structural analysis and description of a system in terms of the causal system's components [3]. This method's results are accomplished by identification and development steps. FCM modelling can provide a cross-network of significant variables and components. The FCM technique determines the need to describe the entire system's scope and limits and quantify the relation between the system components [4]. The FCM analysis yield the following results in this study: (1) Identify and classify system variables into different categories, including economic, environment, legal, political, social, and technological. (2) Evaluating concepts based on their impact on other variables; (3) Draw the parameters' interrelationships according to the specialised knowledge.

Principally, cognitive maps are directed diagrams which have two major components: (1) variables (known as nodes) to describe the system components and behaviours, and (2) links (known as edges) to represent the links and interrelationships between the nodes. Links between the nodes are assigned weights to quantify the strength of their causal associations. The fuzzy logic added to cognitive maps demonstrates the degree of uncertainty involved in human thought. The addition of fuzzy numbers enables highlighting the level of influence and impact that concepts have on other concepts and the system, resulting in higher investigation efficiency. In an FCM, concepts take the fuzzy values in the range between (0,1) (or (-1,1) [5]) and weights of the arcs/interconnections belong to the

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interval (-1,1) [6]. This presents vague degrees of causality between hazy casual concepts. There are three different types of possible causalities ($R_{ij}$) between every pair of concepts $C_i$ and $C_j$:

$R_{ij}>0$: positive causality, where $C_i$ casually increases $C_j$,

$R_{ij}<0$: negative causality, where $C_i$ casually decreases $C_j$, and

$R_{ij}=0$: no causality between $C_i$ and $C_j$.

The logic of an FCM developed upon dynamic feedbacks refers to forward iterations. A mathematical formulation is designated to measure the values of the corresponding variables for each concept. Typically, an FCM of n concepts could be represented mathematically by a n state vector: (A) which gathers the concept's values and by a n×n weight matrix (W). Having assigned values $A_i$ to the concepts $C_i$ and weight among concepts, the FCM converges to an equilibrium point using below calculation rule:

Rescaled-Kosko interference:

$$A_i^{(s+1)} = f\left((2 \times A_i^s - 1) + \sum_{j=1, j\neq i}^{n} w_{ji} \times (2 \times A_j^s - 1)\right) \quad (1)$$

Kosko [7] has introduced an iterative equation which was further developed by Papageorgiou [8] to calculate the values of the concepts at each iteration (Eq. 1). This equation is known as rescaled-Kosko interference. Where $s$ is the interaction index an every simulation step; $A_i^{(\kappa)}$represent the value of concept $C_i$ at the simulation step $s$ ; and $w_{ij}$ illustrates the weight of the interconnection between concept $C_i$ and concept $C_j$. The simulation process is initiated by assigning values to nodes to be transformed through the simulation process. Accordingly, fuzzy values are assigned to concepts, and, as a result, all concepts store specific numeric values. Necessarily, transformation functions are required to retain fuzzy causal edges between -1 to +1. Generally, there are four most commonly used transformation functions: hyperbolic tangent, trivalent, and linear Sigmoid [9]. Linear Sigmoid function (Eq. 2) was selected in this study as the transition function due to its reliability and accuracy [10].

Linear Sigmoid: $f(x) = \frac{1}{1+e^{-\lambda \times x}}$ (2).

## III. Research Methodology

The FCM method was a progressive procedure with two main steps (Figure 1): (I) recognition of concepts, (II) FCM expansion and analysis. The first stage included a literature review, surveys, compiling the outcome of the surveys, and lastly, finalising the picked concepts. Upon defining the study's purpose and scope, a preliminary list of influential parameters in the wind sector was initially identified from the literature review. The overall trend of wind energy deployment refers to the electricity generated by turbines in onshore wind farms.

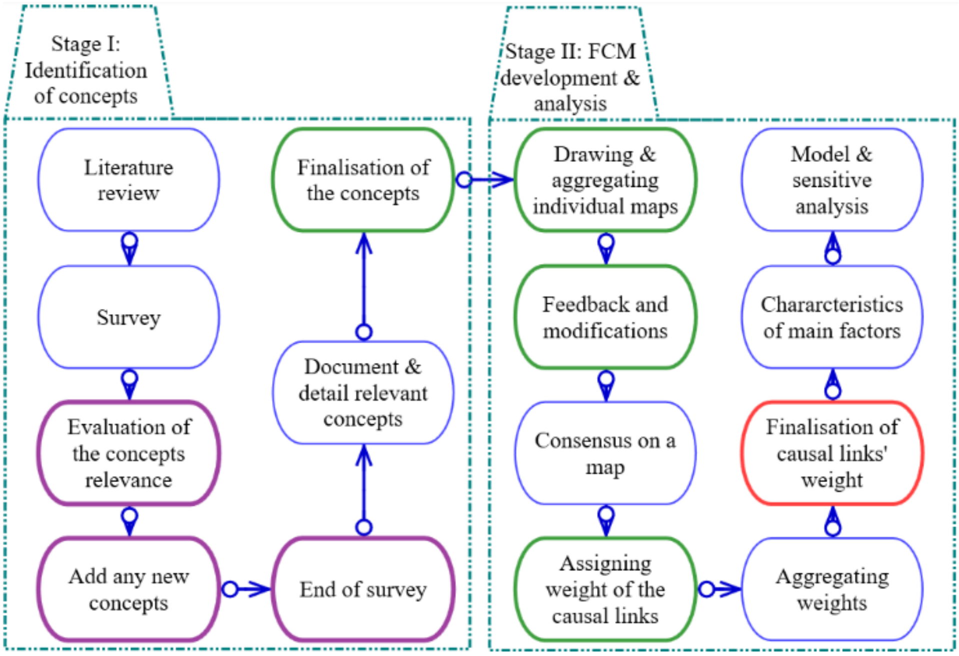


*Figure 1.Proposed framework. Blue cells: Authors activity; Purple cells: Questionnaire surveys; Green cells: Expert engagements; Red cell: Expert group consultation.*

The discovered variables were grouped into six main categories of the PESTEL framework [11]: political, economic, social, technological, environmental, and legal. These concepts were then given to respondents through a questionnaire survey to estimate their relevance. This categorisation strived at (1) improving the weights assigned, (2) helping the respondents of the questionnaires to find any lost concepts within each category, and (3) gaining some impressive generalised results. One hundred and forty postgraduate students in energy engineering and foresight from top-ranked universities of Iran were asked through email to evaluate the association level between 36 parameters and the object by a 7-point bipolar Likert scale and add any missed variable with its connection degree at the end of each main section. The response rate was 26.4% (37 replies). The collected values of each concept were accumulated. Those rated as 'moderate connection' or above were given to the experts in the last step of stage I (finalisation of the concepts).

A group of 15 expert stakeholders firstly were familiarised with the case and the FCMs. Next, the ascertained factors were distributed to the professionals for further estimation. The factors were discussed, modified, merged, and filtered to ultimately reach 26 concepts (72.2% of the initial concepts; Table 1).

*Table 1. Main categories and concepts*

| *Main factor* | *#* | *Concept* |
|---|---|---|
| *Economic* | $EC_1$ | *Economic stagnation** |
| | $EC_2$ | *Electricity demand* |
| | $EC_3$ | *Operating expenses* |
| | $EC_4$ | *Electricity price* |
| | $EC_5$ | *Investment risk* |
| | $EC_6$ | *Return on investment* |
| | $EC_7$ | *Budget provision* |
| | $EC_8$ | *Exchange rate* |
| | $EC_9$ | *Electricity export* |
| | $EC_{10}$ | *Energy price liberalization* |
| | $EC_{11}$ | *Private sector disengagement** |
| *Environment* | $EN_1$ | *Environmental regulations* |
| | $EN_2$ | *Environmental concerns* |
| *Legal* | $LE_1$ | *Market regulations* |
| | $LE_2$ | *Government supports** |
| | $LE_3$ | *Guaranteed electricity purchase* |
| | $LE_4$ | *Disruption of administrative* |
| *Political* | $PO_1$ | *Unstable relations with the U.S.** |
| | $PO_2$ | *Unstable relations with EU* |
| | $PO_3$ | *Sanctions** |
| | $PO_4$ | *Regional & domestic instability* |
| *Social* | $SO_1$ | *Population growth* |
| | $SO_2$ | *Public knowledge* |
| *Technological* | $TE_1$ | *Technology maturity* |
| | $TE_2$ | *Local technical development* |
| | $C_{26}$ | *Deployment of wind energy* |

* Key concepts

After agreement on the concepts, they were requested to draw individual maps. The personal maps were assembled, and a preliminary cognitive map depicting the consensus viewpoint was presented. The aggregated map was declared to the panel to obtain feedback and possible changes to gain consensus on the map. Then stakeholders weighted the causal links conveniently using either (1) numerical coding using values within the range of -1 (most significant negative) and +1 (most significant positive) or (2) linguistic terms that indicate the identical quantitative values. The gathered assessments were combined by averaging the causal weights. The aggregated weights were used (the red cell in Figure 1) in an online meeting with the entire expert stakeholder group to finalise the links and arrive at an agreement on the final cognitive map. Finally, various aspects of the developed FCM were investigated, and the properties of the main categories and model structure were analysed, and the sensitivity of the key concepts was measured.

## *A.* Revealing Key Concept

Narrowing the variables to the most central and uncertain items sets value on the analysis when there are too many parameters with a minor role in the system's dynamics. In identifying key concepts, the experts' viewpoints are consolidated into the model's characteristics. Three indices obtained from the FCM highlight these characteristics: in-degree, outdegree, and centrality. These indexes were measured to define the concept's role in the model. The first two indicate the weight of the inbound and outbound links. They are recognised as the driver (influential or active) and receiver (dependent or passive). Centrality measures the overall importance of a concept to the causal flow on the cognitive map by calculating the absolute sum of interactions between concepts [7]. Concepts with the highest centrality after experts' approval were elected as key concepts. More information and characteristics of the model are presented as following.

# IV. RESULTS

The main factors features, model structure, and sensitivity analysis of the key concepts are presented in the following sections.

## *A.* Analysis of the PESTEL Factors

The main factors outline particular features when studying the aggregate value of their corresponding concepts. While they were not employed in the FCM simulations, they do provide dominant penetrations toward two overall trends: First, the central aspects of the main factors (Figure 2), and second, the macro connection that exist between them (Table 2. Twenty-eight interlinkages between the PESTEL factors.).When self-loops are included, social and environmental factors have the most negligible impact on the system, while legal, economic, and political categories are the most influential with the highest centrality (6.4, 6.39 6.13, respectively) (Figure 2). The technological aspect will play a limited role (2.65) in the growing wind energy, as expected. The political factor is more of a transmitter than a receiver (5.03 > 1.10), in contrast to the economic factor's passive role. When exogenous dynamics are excluded, wind energy expansion is dominated by legal and technological categories, which have the highest centrality (5.1 and 4.8, respectively). As the least active and most influential factors (0.05 and 3.98), political parameters fall to the third level. A large proportion of economic factors are self-loops (52%) as they become more receivers than transmitters (2.11 > 1.23), and social and environmental categories are the two lowest rated with the lowest centrality.

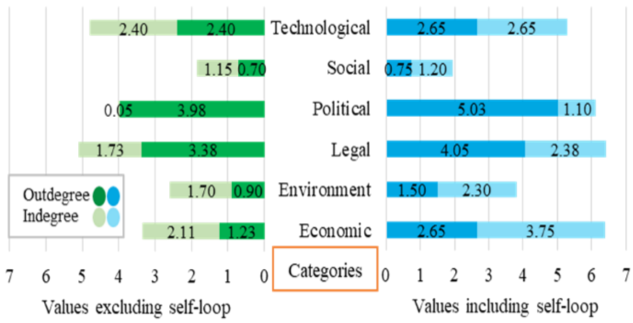


*Figure 2. Outdegree and in-degree values of the PESTEL categories, including and excluding self-loops.*

Concepts within all groups associate with others, meaning there is no solely dependent category (Table 2). As the most active group, the economic factor is a significant receiver concerning the political and legal considerations (12.1 and 9.5, respectively). This indicates that political and legal variations powerfully shape the financial determinants. The political factor influences two other variations, environment and legal, while playing a minor role as a receiver from the economic factor (0.2). The legal factor does not direct the political elements, but it changes technological and social variables. The synergy between the environment category and four others designates its almost active role in the system.

*Table 2. Twenty-eight interlinkages between the PESTEL factors.*

| Categories | Economic | Environment | Legal | Political | Social | Technological |
|---|---|---|---|---|---|---|
| Economic | 15.3 | 1.6 | 4.4 | 0.20 | 0.5 | 2.8 |
| Environment | 0.1 | 1.2 | 0.1 | | 1.0 | 0.6 |
| Legal | 9.5 | 0.4 | 2.6 | | 0.7 | 1.4 |
| Political | 12.1 | 0.8 | 1.9 | 4.20 | | |
| Social | 0.6 | 0.6 | 0.2 | | 0.1 | |
| Technological | 3.5 | | 0.3 | | 0.1 | 0.5 |

## *B.* Model Structure

The FCM model (Figure 3) involves 26 concepts and is arranged into six PESTEL categories. Around 42% of concepts refer to the economic group, while the legal, social, and technological factors possess the lowest share (8%). There are 185 linkages among concepts, including three positive self-loops in the economic and social categories. Environmental and social indicators do have a direct influence on goal whilst nine economic concepts, three political and legal, and two technological concepts directly impact the goal. Deployment of wind energy only transforms electricity exports directly. Experts opted for five key concepts amongst seven parameters with the highest centralities that significantly impact the system. Two come from the economic category (EC1 and EC11), one is legal (LE2), and the other two are political (PO1 and PO3). Within the FCM model, private sector disengagement has the most control over other concepts (7.7), whereas government support and sanctions are strongly influenced by other determinants (9.2 and 7.5, respectively). The highest centrality and outdegree among all concepts belong to the government support that proves the government's fundamental influence on wind energy spread. Unstable relations with the U.S. was preferred by the specialists for their significant influence on the system (7.30), although budget provision and investment risk had higher centrality (8.1 and 7.8). All concept types are ordinary (no being isolated concept), which means they are in relation to at least one concept in the network.

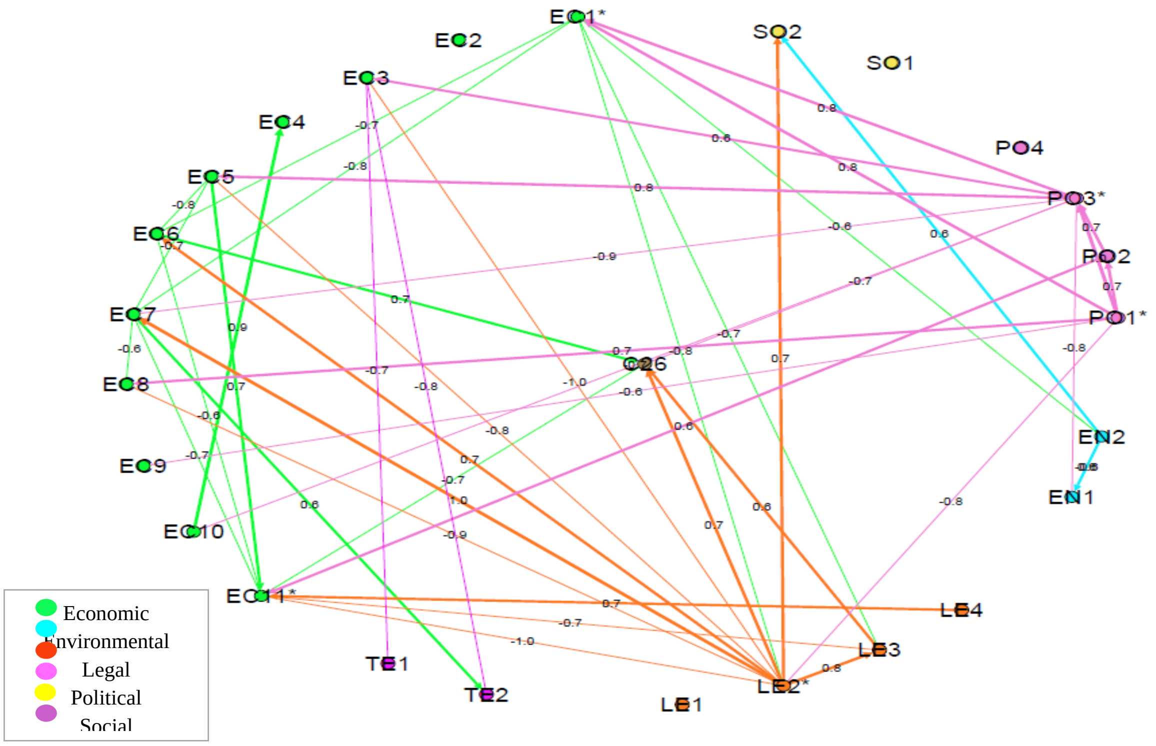


*Figure 3. The finalised FCM visualised by Gephi, illustrating only nodes with the weights >= 0.5 (+/-).*

Three useful guides promote the perception of the performance of the network and its concepts. Closeness centrality calculates the distances from a vertex to the other concepts [12]. The eigenvector centrality measures the impact of a concept in a network as the extension of the degree centrality, and harmonic centrality assesses the average distance of a concept to other connected or unconnected nodes. As Figure 4 demonstrates, the network connections indicate that the concepts' harmonic and closeness centrality are approximately equal. It confirms the connectivity of the network. Economic stagnation ($EC_1$), which has the greatest harmonic and closeness centrality, is actively correlated to other concepts while its eigen centrality is lower than 0.1. The highest eigen centrality level for private sector disengagement ($EC_{11}$) displays its meaningful impression on the system. High closeness and harmonic centrality for both unstable relations with the U.S. and sanctions ($PO_1$ and $PO_3$) explain their dynamic cooperation with the system's other components.

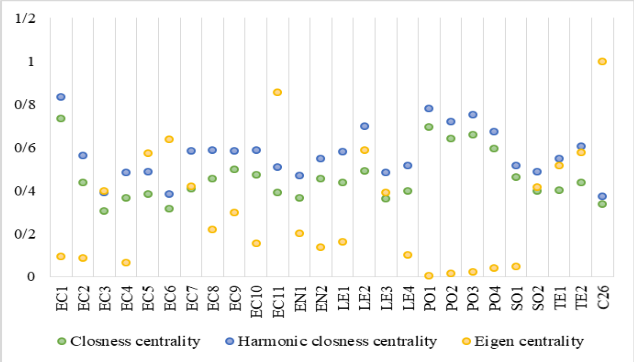


*Figure 4. Analysis of the concepts' performance using three network indices.*

## C. Sensitivity Analysis

The sensitivity of the model is checked here to assess the consequences of a key concept's modifications on the system and goal. For this purpose, the model is run to create the initial steady state. Its results of no intervention with a starting vector at one were reached after less than 25 iterations. Key concepts sensitivity was then derived by analogising the relative variations between the obtained steady state and a new one.

To better appreciate the concepts' respond to the changes, the impact of each key variable alteration on the system in isolation is considered (Figure 5). The highest qualification level is observed when sanctions, unstable relations with the U.S., and economic stagnation values are clamped to 0. A reduction in economic stagnation generates a sizeable relative increase in the return on investment and operating expenses (+46% and -34%, respectively). Sanctions and unstable relations with the U.S. shift the value of 14 and 18 variables (> 5 %), respectively. Such key concepts adversely influence $EC_{11}$ and $EC_5$ by almost identical values. These changes are nearly correlated to the return on investment rise and the economic stagnation fall. The lack of government support leads to a rise in private sector disengagement and investment risk of about 9%. When clamping private sector disengagement to 0, concepts profoundly stabilized except for budget provision and local technical development. Private sector disengagement is also most stimulated by $EC_1$, $PO_1$, and $PO_3$ at around -39%, -36%, and -40%, respectively.

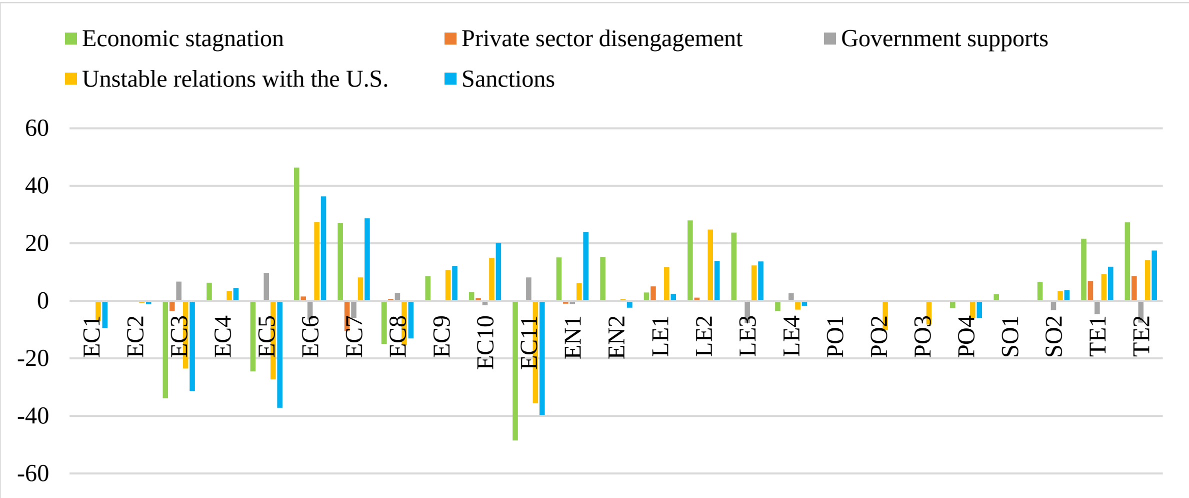


*Figure 5. The comparison between steady-state and change rate of 25 concepts by clamping each key concept to 0.*

The target variable's fluctuation is compared to its steady-state value when the key concepts reach 0 (Table 3). Wind energy usage is reduced to zero with a 90% reduction in government support, and its significant performance in the system is marked. On the contrary, the general orientation shows that sanctions and recession control the dynamics of the main concept by providing an ideal value of +68%. The slight positive effect of private sector disengagement improves the wind energy situation to + 33%, and promotion in relations with the U.S. will expand wind energy by 55% in the country.

*Table 3. The sensitivity of the goal (C26) by clamping each key concept from 1 to 0.*

| Key concepts | Value of goal (C26) when a key concept is clamped from 1 to 0 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 0.9 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.3 | 0.2 | 0.1 | 0 |
| Economic stagnation | -0.09 | 0.02 | 0.13 | 0.24 | 0.33 | 0.42 | 0.50 | 0.56 | 0.61 | 0.64 | 0.68 |
| private sector disengagement | -0.10 | -0.06 | -0.01 | 0.04 | 0.08 | 0.13 | 0.17 | 0.21 | 0.25 | 0.29 | 0.33 |
| Government supports | 0.65 | 0.61 | 0.56 | 0.50 | 0.42 | 0.33 | 0.22 | 0.10 | -0.03 | -0.15 | -0.26 |
| Unstable relations with the U.S. | -0.26 | -0.20 | -0.13 | -0.05 | 0.03 | 0.12 | 0.22 | 0.31 | 0.40 | 0.49 | 0.55 |
| Sanctions | -0.08 | 0.02 | 0.13 | 0.23 | 0.33 | 0.41 | 0.49 | 0.55 | 0.60 | 0.64 | 0.67 |

## V. DISCUSSION and CONCLUSION

An FCM method was applied to investigate the specifications and predictable future of the wind sector in Iran. Thirty-six concepts that may influence was derived from the literature review to develop the map. The recognised concepts relationship was examined in an online survey before being confirmed by specialists' opinions. Twenty-six concepts were finalised and divided into the six PESTEL categories. Results determine that the country's wind energy development is dominated by economic and legal concepts with robust interconnections. Conversely, social and environmental concepts are the least authoritative operators. Five key factors are two political (sanctions, unstable relations with the U.S.) and one economic (economic stagnation) concepts that dominate the system’s maturity.

In selecting the FCM technique, diverse criteria were regarded: (1) handling a complicated issue at a strategic level that was intermingled with macro determinants, (2) dealing with a non-linear problem, (3) modelling a proper long-term issue with high uncertainty, and (4) delivering meaningful outcomes without widespread data. Energy systems' investigation was administered through a broad spectrum of mathematical and statistical approaches [13, 14]. Absolute mathematical methods cannot obtain uncertainties and are more beneficial for short-term evaluations [15]. Energy system models are proper for long-term assessments but only when there are large data from several sectors. These methods concentrate on the final foresight results using quantified parameters while their causality and evolvements are not into account. Simulation modelling procedures address the system's feedback dynamics and have been well studied in the energy domain [14, 16-18]. FCM is helpful in scientific data shortage, and the concepts are holistic and unintelligent. The simple nature of this method is easily user-friendly for politicians, but it is powerful for magnifying to obtain high abstraction of complex issues. Although the result of its simulation is useful for understanding and insight into the system, the diversity of views of mental models provides a sufficient future trend (s). As an emerging tool in this field, further research can demonstrate the applicability of FCM.

This research did not investigate the next decision-making process that could effectively handle and counterbalance the uncertainties. Finding strong beneficial policies will not be an easy assignment as the majority of the uncertainties are exogenous. The scenarios facing the Iranian wind industry concerning various economic, political and social conditions that were identified as the most important indicators have not been studied in this paper, and can be discussed as an important issue in future research to familiarise politicians with the possible conditions of this industry. What politicians of the RE sector can realistically discover and pursue hidden connections and gaps between economic and legal determinants. In doing so, it is essential to focus on long-term contracts and legal obligations that guarantee financial benefits to private businesses. Another solution to the natural uncertainty that minimizes political change's engagement is transforming the cash flow by finding alternative and more sustainable case sources.

Finally, two observations can be obtained from the developed model. The two-stage process to recognise the concepts aimed to identify all aspects related to the main issue. However, the concentration on macro behaviours at the top layer inevitably neglected possible micro-and meso-level connections and their interlinkages with the economic and private sectors. This was inevitable to maintain the same level of investigation for all parameters. Future studies can outline more sub-maps that consider these missing links and combine them into a multi-layer map correlating micro-, meso- and macro-level analyses. Future work could also focus more attention on the critical exogenous economical-political elements.

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