International Journal of Applied Operational Research
Vol. 14, No. 4, pp. 1-19, 2026

Journal homepage: www.ijorlu.ir

Governance-based sustainability assessment of Iran's electricity energy management system: A two-level ANFIS approach

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Received: 7 July 2026 ; **Accepted:** 13 August 2026

Abstract
Governance sustainability plays a critical role in improving the performance of electricity management systems, particularly in countries facing structural energy challenges. This study develops a two-level Adaptive Neuro-Fuzzy Inference System (ANFIS) framework to assess the sustainability of governance in Iran's electricity management system. The proposed model is structured around six governance sub-dimensions: energy policy, governance quality, institutional stability, energy security and diplomacy, crisis and demand management, and transparency and corruption. A structured questionnaire was designed based on the identified governance indicators and completed by 137 qualified energy experts. The collected data were divided into training, testing, and validation datasets, and Gaussian membership functions were applied within the ANFIS structure. The results indicate that energy policy has the highest contribution to governance sustainability (0.231), followed by crisis and demand management (0.196), energy security and diplomacy (0.182), institutional stability (0.164), governance quality (0.135), and transparency and corruption (0.092). At the indicator level, pricing policies, demand management, subsidy policies, political stability, energy policies, crisis preparedness, and economic stability obtained the highest relative weights. These findings suggest that improving governance sustainability in Iran's electricity sector requires greater attention to pricing reform, subsidy adjustment, demand-side management, crisis preparedness, and institutional stability.

Keywords: Governance Sustainability, Electricity Energy Management, ANFIS, Energy Policy, Demand Management, Iran.

1 Introduction

Energy management has evolved into a complex governance challenge shaped by climate pressures, resource constraints, geopolitical instability, and growing demand [1]. Contemporary energy systems are therefore expected to ensure supply reliability, affordability, environmental sustainability, and resilience simultaneously. The energy trilemma captures this challenge by

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[DOI: 10.71885/ijorlu-2026-4-737]

connecting energy security, equity, and sustainability [2], while empirical studies have demonstrated the relationships of these dimensions with economic growth and investment [3, 4]. Consequently, energy governance extends beyond technical management to encompass policy quality, regulatory stability, institutional coordination, transparency, accountability, and crisis preparedness [5]. The effectiveness of such governance depends not only on policy design but also on institutional capacity, implementation effectiveness, and public legitimacy [6-8]. Emerging technologies, including blockchain, have also been proposed as mechanisms for improving transparency and traceability in supply chains, making them relevant to the transparency and corruption-related governance dimension examined in this study [9]. These challenges are particularly pronounced in resource-dependent developing economies, where abundant fossil-fuel resources may coexist with inefficiency, subsidy burdens, and investment constraints. Under such conditions, resource abundance may strengthen national capacity when supported by effective institutional coordination or intensify systemic fragility when such coordination is lacking. The transition toward more sustainable energy systems thus depends on the interaction of institutions, actors, technologies, and markets [10,11].

Iran provides a clear example of this complexity. Despite its substantial energy resources, the country continues to experience persistent energy imbalances, including winter gas shortages, summer electricity deficits, and year-round pressure from gasoline demand [12]. These problems are reinforced by distorted subsidy structures, increasing peak demand, and inadequate investment in energy infrastructure [5]. Iran's energy crisis should therefore be understood not only as a supply–demand imbalance but also as a broader governance and transition challenge. Gradual and credible electricity subsidy reforms may reduce both energy demand and emissions [13], whereas the limited development of renewable energy reflects institutional weaknesses and credibility constraints [14]. In contrast, coordinated and mutually reinforcing reforms may create the conditions required for deep decarbonization [15]. Governance indicators should consequently be treated as active determinants of crisis preparedness and response rather than as peripheral contextual factors.

Sustainability indicators provide a structured basis for examining these interconnected challenges. They encompass economic factors such as pricing and investment; social factors such as access and affordability; environmental factors such as emissions and dependence on fossil fuels; technical and infrastructural factors such as grid reliability and energy losses; and governance and institutional factors such as policy effectiveness, coordination, and transparency [16]. Energy sustainability does not result from any single dimension but emerges through the interaction among them. Within this multidimensional structure, governance occupies a central analytical position because it influences pricing reform, investment allocation, infrastructure modernization, environmental enforcement, demand management, and crisis anticipation [1]. In this sense, governance constitutes the mechanism through which sustainability objectives are translated into coordinated and implementable policies.

Conventional assessment techniques, including simple scoring systems, linear aggregation, fixed-weight multi-criteria decision-making methods, and static scenario rankings, may not adequately represent the nonlinear relationships, feedback mechanisms, and context-dependent interactions that characterize energy systems. Multi-criteria decision-making approaches, including hybrid techniques that integrate group voting with the analytical hierarchy process, have nevertheless demonstrated their usefulness in sustainability-related selection problems across different domains [17]. However, their limitations become particularly important in governance-centered crisis assessments, where improvement in one institutional factor may produce little effect unless complementary governance conditions are also strengthened. The Adaptive Neuro-Fuzzy Inference System (ANFIS) offers an appropriate intelligent modeling approach for addressing this complexity. By combining neural-network learning capabilities with fuzzy inference, ANFIS can accommodate quantitative and qualitative information as well as uncertain, nonlinear, and interdependent indicators, including those associated with governance. Recent applications have demonstrated its capacity to model complex patterns in energy demand and renewable-energy integration [18,19]. Moreover, recent reviews of artificial intelligence applications have highlighted the increasing importance of explainable and governance-aware modeling frameworks [20,21].

Taken together, the recent literature suggests that Iran's energy imbalance cannot be adequately understood or addressed solely as a technical supply–demand problem. Rather, it reflects a broader governance challenge involving policy effectiveness, institutional coordination, regulatory credibility, investment capacity, transparency, and crisis preparedness. Although previous studies have examined specific aspects of Iran's energy transition or employed scenario-based and system-dynamics approaches, limited attention has been devoted to systematically modelling how governance conditions interact under uncertainty to influence energy sustainability during crises. This gap establishes the need for an integrated and governance-centered assessment framework.

To address this gap, the present study conceptualizes governance sustainability as a multidimensional construct whose overall performance depends on the combined effects of its constituent dimensions. Theoretically, it explains how governance conditions collectively shape sustainability outcomes in the energy sector, extending the analysis beyond the mere identification of relevant indicators. Methodologically, it combines fuzzy Delphi-based indicator validation with a two-level ANFIS structure, through which dimension-specific evaluations are synthesized into an overall governance assessment. This integration translates expert knowledge into an empirically grounded decision-support model capable of representing nonlinear relationships, interdependencies, and uncertainty.

2 Literature review

2.1 Energy governance and multidimensional sustainability

Energy management has expanded beyond the technical coordination of energy production and consumption to encompass economic efficiency, social equity, environmental protection, infrastructure reliability, and institutional capacity. This broader perspective is reflected in the energy trilemma, which frames energy sustainability through the simultaneous pursuit of energy security, affordability and equity, and environmental sustainability [2]. Empirical evidence further indicates that the balance among these dimensions affects economic growth, investment, and environmental performance [3,4].

Achieving such a balance is particularly difficult under crisis conditions. Energy shortages, price volatility, geopolitical disruptions, infrastructure failures, and climate-related pressures can expose weaknesses that remain less visible under normal operating conditions. Energy resilience therefore depends not only on the availability of physical resources but also on the ability of institutions to anticipate disruptions, coordinate responses, adapt policies, and maintain public confidence. In resource-dependent developing economies, abundant fossil-fuel resources may coexist with inefficient consumption, extensive subsidies, limited investment, and weak incentives for technological change. Whether resource abundance strengthens energy capacity or intensifies systemic vulnerability consequently depends on the interaction among institutions, policy actors, technologies, and markets [10,22].

The multidimensional nature of energy sustainability requires assessment frameworks that cover the economic, social, environmental, technical-infrastructural, and governance-institutional dimensions. Economic indicators generally address pricing structures, subsidies, investment, productivity, and financial viability. Social indicators measure affordability, access, energy poverty, public welfare, and the distributional effects of energy policies. Environmental indicators focus on emissions, carbon intensity, fossil-fuel dependence, and resource consumption, whereas technical indicators represent generation adequacy, network reliability, transmission losses, and renewable-energy integration. Governance indicators assess policy effectiveness, regulatory quality, institutional coordination, transparency, accountability, and implementation capacity [1,16].

These dimensions are closely interdependent. For example, electricity-pricing reform may improve economic efficiency and reduce demand but can also weaken affordability unless it is accompanied by appropriate social protection. Renewable-energy development may reduce emissions but requires investment capacity, regulatory stability, grid readiness, and credible long-term policies. Similarly, infrastructure modernization can enhance reliability, although its effectiveness depends on financing arrangements and institutional coordination. Sustainability assessment should therefore consider how these dimensions interact rather than evaluating them as isolated components. Assessments limited to technical or environmental performance may overestimate the feasibility of reforms by overlooking their social, financial, and institutional requirements.

Governance occupies a central position in this structure because it determines how sustainability objectives are translated into policy instruments and implemented in practice. Policy effectiveness converts strategic objectives into executable programs; regulatory quality shapes investor confidence; institutional coordination aligns the activities of governmental and sectoral organizations; transparency and accountability support legitimacy; and stakeholder participation facilitates public cooperation with demand-management and pricing policies. Governance thus influences both the direction of energy reforms and the capacity of the system to sustain them over time [6]. Evidence from multidimensional governance research also demonstrates that integrated and participatory institutional arrangements can contribute to stronger policy performance [7, 23].

2.2 Governance and sustainability challenges in Iran's electricity sector

Iran illustrates the complexity of governing a resource-rich energy system under persistent structural pressure. Despite substantial hydrocarbon reserves and considerable renewable-energy potential, the country experiences recurring electricity deficits in summer, natural-gas shortages in winter, and sustained pressure from gasoline consumption. These imbalances reflect the combined effects of rapidly increasing demand, distorted price signals, insufficient investment, aging infrastructure, and fragmented policy responses [12]. System-dynamics evidence also suggests that Iran's electricity shortage cannot be resolved through isolated supply-side interventions because consumption, subsidies, investment, generation capacity, and institutional decisions interact over time [5].

Subsidized energy prices constitute a major component of this challenge. Although subsidies can protect short-term affordability, they may encourage excessive consumption, weaken the financial position of electricity-sector organizations, and reduce the resources available for infrastructure investment. Research indicates that gradual and credible subsidy reform can lower future electricity demand and cumulative emissions while improving the competitiveness of renewable-energy technologies [13]. Nevertheless, the practical success of reform depends on public trust, transparent implementation, social compensation, policy continuity, and institutional capacity. Pricing reform is therefore simultaneously an economic, social, and governance issue.

The limited progress of renewable energy provides another example of the importance of governance. Renewable-energy expansion requires more than technical potential; it also depends

[DOI: 10.71885/ijorlu-2026-4-737]

on regulatory credibility, stable investment conditions, institutional coordination, and alignment among public organizations and market actors. Institutional uncertainty and inconsistent policy incentives have constrained the development of renewable energy in Iran [14]. Conversely, coordinated strategies integrating renewable-energy expansion with electricity-subsidy reform may reduce demand, alter the generation mix, and facilitate deeper decarbonization [15].

Iran's electricity crisis consequently represents a governance and transition challenge rather than a technical supply–demand imbalance alone. Energy policies must reconcile affordability with financial viability, investment needs with economic constraints, environmental targets with fossil-fuel dependence, and immediate crisis response with long-term transition objectives. Institutional fragmentation further complicates this process because electricity, natural gas, fuel, environmental, and economic policies are managed by different organizations whose responsibilities and priorities may not be fully aligned.

Under these conditions, governance indicators function as active determinants of energy-system performance. Policy effectiveness influences whether reform programs are translated into implementation; political and economic stability affect investment confidence and policy continuity; regulatory predictability shapes private-sector participation; energy security and diplomacy influence resource and technology access; crisis preparedness determines the capacity to respond to shortages; and transparency affects institutional legitimacy. The sustainability of electricity management in Iran must therefore be evaluated through a framework capable of representing the combined influence of these governance conditions.

2.3 Research gap and positioning of the study

The reviewed literature offers important but dispersed insights into energy sustainability, governance, crisis management, scenario planning, and intelligent modelling. Energy-trilemma research explains the need to balance security, equity, and environmental sustainability, while multidimensional assessment studies provide indicators for evaluating economic, social, environmental, technical, and institutional performance. Governance research identifies policy effectiveness, regulatory quality, coordination, stability, transparency, and accountability as essential conditions for successful energy transitions. Scenario and system-dynamics studies also demonstrate that Iran's energy imbalance results from interacting policy, demand, investment, and infrastructure factors rather than a single technical deficiency.

Three limitations remain apparent. First, many sustainability assessments incorporate governance as one dimension among several without examining the internal structure and interactions of governance indicators. Second, studies of Iran's energy imbalance mainly focus on transition pathways, supply–demand scenarios, subsidy reform, or system dynamics and pay less attention to the integrated evaluation of governance sustainability. Third, conventional assessment methods often depend on fixed weights or additive relationships and may therefore overlook the conditional, uncertain, and nonlinear effects of governance variables.

The present study addresses these limitations by conceptualizing governance sustainability as a multidimensional and nonlinear construct. It focuses on six governance sub-dimensions: energy policy, governance quality, institutional stability, energy security and diplomacy, crisis and demand management, and transparency and corruption. The indicators associated with these sub-dimensions are initially selected and validated through the fuzzy Delphi method, thereby ensuring that the evaluation structure reflects expert knowledge and the institutional characteristics of Iran's electricity sector.

Methodologically, the validated indicators are incorporated into a two-level ANFIS framework. At the first level, separate sub-ANFIS models transform the relevant indicators into dimension-specific governance assessments. At the second level, the outputs of these models are

[DOI: 10.71885/ijorlu-2026-4-737]

combined to estimate overall governance sustainability. This structure moves beyond the independent ranking of indicators by modelling their combined and nonlinear effects while preserving an interpretable decision-support framework. Accordingly, the study contributes to the literature by integrating expert-based indicator validation with adaptive neuro-fuzzy modelling and by explaining how governance conditions collectively shape the sustainability of electricity energy management under crisis conditions.

3 Research methodology

This study adopts an applied quantitative modelling approach to assess the sustainability of governance in Iran's electricity energy management system. The methodology follows the hierarchical structure of the proposed model, in which governance sustainability is evaluated through several sub-dimensions and their associated indicators. The research process comprised three main stages: identifying and classifying governance indicators, validating them through expert judgement, and collecting and preparing data for ANFIS-based modelling.

The indicator-validation panel consisted of 21 purposively selected experts in energy management, electricity policy, public governance, energy economics, and sustainable energy systems in Guilan Province, Iran. The panel included university faculty members, senior managers, policy specialists, and professionals from energy-related organizations, including electricity companies, energy-planning institutions, and regulatory bodies. Participants were selected based on their relevant academic qualifications and managerial, research, policymaking, or professional experience. The diversity of their institutional roles was intended to incorporate both academic and practical perspectives into the validation process.

The initial indicators were identified through a review of the relevant literature and subsequently refined and validated using the fuzzy Delphi method. The experts evaluated the relevance and appropriateness of each indicator using linguistic judgments, which were converted into triangular fuzzy numbers and aggregated to determine the level of expert consensus. Indicators meeting the 0.7 acceptance threshold were retained, whereas those below the threshold were revised or excluded.

Following indicator validation, a structured questionnaire was administered to a broader group of qualified respondents from the same professional fields. Respondents evaluated the indicators using a five-point Likert scale ranging from "Very Low" (1) to "Very High" (5), resulting in 137 valid questionnaires. The 21-member panel was therefore used specifically for indicator validation, whereas the 137 respondents provided the observations required for ANFIS modelling. The hierarchical architecture also limited the number of inputs processed simultaneously by each sub-ANFIS model, thereby reducing model complexity compared with a single model that includes all indicators. After screening, the dataset was randomly divided into three mutually exclusive subsets: 70% for training, 20% for testing, and 10% for validation, enabling model estimation and evaluation on separate observations.

3.1 Adaptive Neuro-Fuzzy Inference System (ANFIS)

The Adaptive Neuro-Fuzzy Inference System (ANFIS), introduced by Jang (1993) [24], combines fuzzy if–then rules with neural network learning to model nonlinear relationships between inputs and outputs. By integrating fuzzy logic with data-driven learning, ANFIS can adjust the parameters of a fuzzy inference system through neural network-based training algorithms [25,26]. The selection of membership functions depends on the characteristics of the

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problem. In this study, Gaussian membership functions were used to transform crisp input values into fuzzy sets.

The ANFIS architecture consists of five main layers: fuzzification, rule/product, normalization, defuzzification, and output/summation layers [27]. In the first layer, input membership grades are calculated. The second layer determines the firing strength of each rule, while the third layer normalizes these firing strengths. In the fourth layer, the normalized values are combined with the rule consequents, and the final output is obtained in the fifth layer through summation. In this study, the ANFIS model follows a Takagi–Sugeno fuzzy inference structure.

Rule 1: If a *is* A_1 *and* b *is* B_1, $F_1 = S_1 a + r_1 b + t_1$ (1)

Rule 2: If a *is* A_2 *and* b *is* B_2, $F_2 = S_2 a + r_2 b + t_2$ (2)

Where A_1, A_2, B_1 *and* B_2 represent the membership functions while a and b are input parameters. F_1 *and* F_2 are acquired outputs from the system, whereas s, r, and t are nodal consequent parameters.

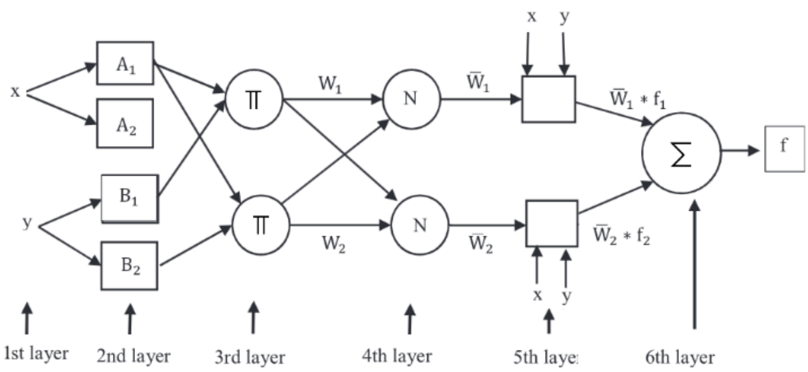

Fig. 1 ANFIS structure with two inputs

ANFIS demonstrates exceptional efficacy due to its ability to provide the necessary dataset, a wide selection of membership functions, robust generalization capabilities, and enhanced interpretability through fuzzy rules. Additionally, it seamlessly integrates linguistic and numerical information for efficient problem-solving [28]. The six operational layers of ANFIS are described in the following [29].

Layer 1: Every node in this layer is the input node where the input variables are passed to other layers. No transaction takes place.

Layer 2: It is the layer where the blur function takes place. The nodes in this layer can be adjusted, and the fuzzy sets belonging to the input variables obtained from the first layer have membership functions. The output of this layer shows the degree of the respective membership functions and is shown in Eq. 3. The most commonly used functions in the literature for the membership function are triangle, trapezoid, generalized-bell, and Gaussian functions.

$$O_{2,i} = \mu_{A_i}(x) \qquad O_{2,j} = \mu_{B_i}(y) \tag{3}$$

Layer 3: It is the rule layer. Each node in this layer represents the rules and numbers created according to the Fuzzy Logic system. For the most preferred classical operator in ANFIS, each node is labeled with the symbol $\prod$ and expresses the product of all input variables as in Eq. 4.

$$w_i = \mu_{A_i}(x)\mu_{B_i}(y) \dots \tag{4}$$

Layer 4: It is the normalization layer. Each node in this layer accepts all incoming nodes in the rule layer as input values, and the normalized trigger level of each rule is calculated in the layer. The formula used in this layer is given in Eq. 5.

$$\overline{w}_i = \frac{w_i}{\sum_{n=1}^{k} w_k} \tag{5}$$

Layer 5: It is the defuzzification and results layer. The weighted result values of a given rule are calculated at each node in this layer. Eq. 6 is used when calculating these result values.

$$O_{4i} = \overline{w}_i f_i = \overline{w}_i(p_i x + q_i y + r_i) \tag{6}$$

Layer 6: It is the output layer of the method. In this layer, the output values from the fifth layer are processed, and the actual value, which is the system's output, is obtained with the result found with the help of Eq. 7.

$$f_{cikis} = \sum_{i=1}^{n} \overline{w}_i f_i = \sum_{i=1}^{n} \overline{w}_i\,(p_i x + q_i y + r_i) \tag{7}$$

4 Results

This section presents the results of the indicator identification and classification process for assessing governance sustainability in Iran's electricity energy management system. Based on the conceptual framework of the study, the governance dimension was structured into several sub-dimensions, each represented by a set of relevant indicators. These indicators provide the input structure for the first-level ANFIS sub-systems and form the basis for evaluating the governance performance of the electricity energy management system. Table 1 presents the final governance indicators, their related sub-dimensions, and the overall dimension used in the proposed model.

Table 1 Main indicators of Governance

Dimension	Sub-Dimension	Indicator
Governance	Energy Policy	Energy Policies
		Renewable Energy Development Policies
		Subsidy Policies
		Pricing Policies
	Governance Quality	Government Effectiveness
		Regulatory Quality
	Institutional Stability	Political Stability
		Economic Stability
		Regulatory Predictability
		Political Risk
	Energy Security and Diplomacy	Energy Security
		Fuel Security
		Network Security
	Crisis and Demand Management	Crisis Preparedness
		Demand Management
		Risk Management
		Institutional Resilience
	Transparency and Corruption	Institutional Corruption

4.1 Defining fuzzy logic system

The proposed framework was designed as a two-level ANFIS model to assess governance sustainability in Iran's electricity energy management system. At the first level, six sub-ANFIS

[DOI: 10.71885/ijorlu-2026-4-737]

systems were developed to evaluate the main governance sub-dimensions. Each sub-system receives its related indicators as inputs and generates a sub-dimensional score as output.

The energy policy sub-system includes energy policies, renewable energy development policies, subsidy policies, and pricing policies. The governance quality sub-system includes government effectiveness and regulatory quality. The institutional stability sub-system includes political stability, economic stability, regulatory predictability, and political risk. The energy security and diplomacy sub-system includes energy security, fuel security, and network security. The crisis and demand management sub-system includes crisis preparedness, demand management, risk management, and institutional resilience. The transparency and corruption sub-system is assessed through the control of institutional corruption indicator.

At the second level, the outputs of these six sub-systems are used as inputs of the main ANFIS model. The final output of the main model is the governance sustainability score, which represents the overall governance performance of Iran’s electricity energy management system. The structure of the main fuzzy system is presented in Figure 2.

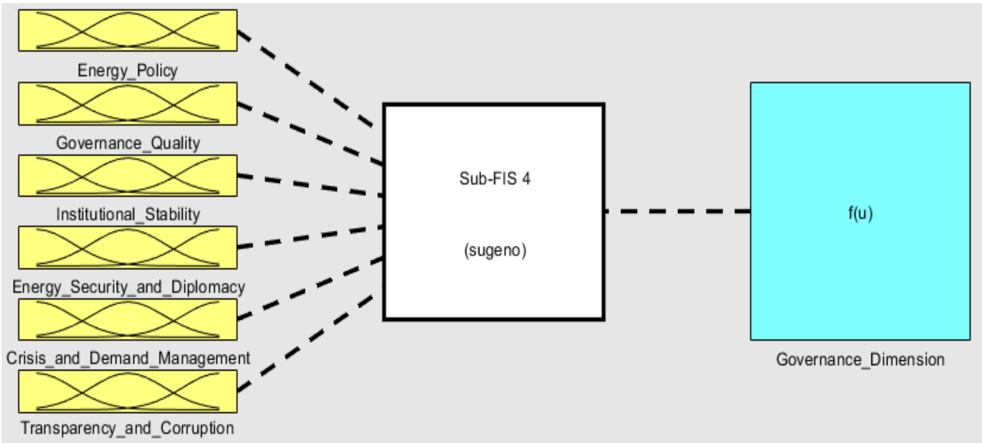

Fig. 2 Structure of the main FIS model

Each governance sub-dimension in the proposed framework is evaluated through a separate sub-ANFIS system, in which the related indicators are used as input variables and the corresponding sub-dimensional score is generated as the output.

4.2 Membership functions

In this study, Gaussian membership functions were selected for all input variables in the ANFIS model. Compared with other membership functions, the Gaussian function provides smooth and differentiable curves, which makes it suitable for modelling continuous input data and supporting the adaptive learning process of ANFIS. The linguistic terms used to represent the variables include Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH).

4.3 Fuzzy rules

The fuzzy rule base was developed to define the relationships between the input indicators and the output score in each ANFIS system. Each rule follows a first-order Sugeno fuzzy inference structure. The antecedent part of the rule includes the linguistic conditions of the input variables, while the consequent part estimates the corresponding output score. The general form of the fuzzy rules For the Main ANFIS system is expressed as follows:

If *Energy Policy is = "…" and Governance Quality is = "…" and Institutional Stability is = "…" and Energy Security is = "…" and Crisis and Demand Management is = "…" and Transparency and Corruption is= "…",* then *Governance Sustainability is= "…".*

Since five membership functions were assigned to each input variable, the number of rules in each ANFIS system depends on the number of input indicators (number of possible rules = 5^n). However, according to the experts, the governance system includes 225 rules, the energy policy sub-system includes 72 rules, the governance quality sub-system includes 25 rules, the institutional stability sub-system includes 78 rules, the energy security and diplomacy sub-system includes 33 rules, the crisis and demand management sub-system includes 83 rules, and the transparency and corruption sub-system includes 5 rules. In the second level, the main ANFIS model receives the six sub-dimensional scores as inputs to estimate the final governance sustainability score. The interface of the governance system is presented in Figure 3.

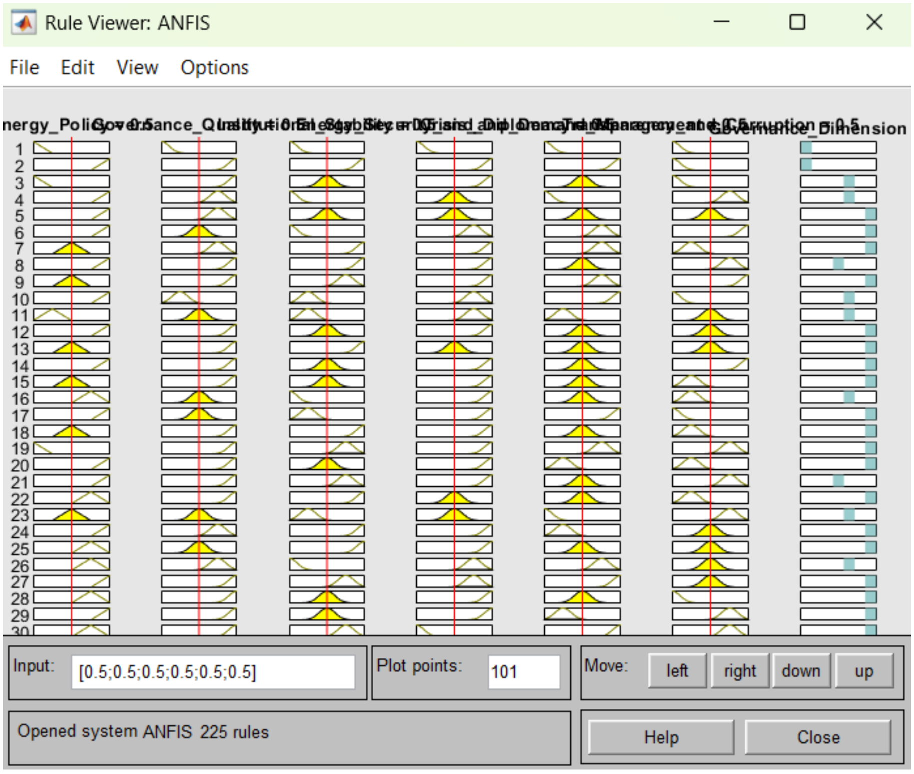

Fig. 3 Graphical representations of the rules for the main ANFIS

4.4 Developing the ANFIS model

-Structure the ANFIS model

The Adaptive Neuro-Fuzzy Inference System (ANFIS) structure used in this study consists of interconnected nodes that transmit information from the input layer to the output layer. Each node performs a specific computational function, and its output is determined by the parameters associated with that node. During the training process, these parameters are updated through the ANFIS learning algorithm to enhance model performance. Based on the proposed two-level framework, six sub-ANFIS models were developed to estimate the governance sub-dimensional

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scores, which were subsequently used as inputs of the main ANFIS model. Figure 4 illustrates the architecture of the main ANFIS system.

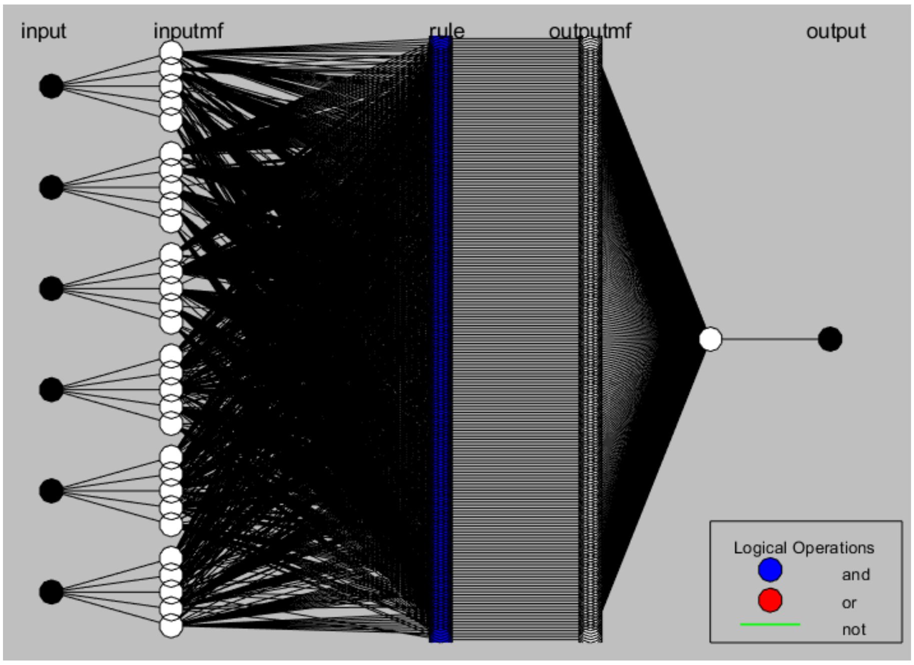

Fig. 4 ANFIS structure of the Main system

The individual structures of the sub-ANFIS models are not presented separately, since they follow the same computational architecture and differ only in terms of their input indicators and corresponding outputs. Therefore, reporting all sub-system diagrams would lead to unnecessary repetition without adding further methodological clarification.

4.5 Data gathering

To train the ANFIS-based governance sustainability model, a structured questionnaire was designed based on the governance sub-dimensions and their corresponding indicators. The questionnaire was distributed among qualified experts in the energy sector, and respondents were asked to evaluate the indicators using a five-point scale ranging from "Very Low" (1) to "Very High" (5). A total of 137 valid questionnaires were collected from eligible experts. The dataset was then divided into three subsets: 70% for training, 20% for testing, and 10% for validation. Accordingly, 96 responses were used for training the model, while the remaining data were assigned to the testing and validation stages.

4.6 Training the fuzzy inference system

In the first stage, the ANFIS and sub-ANFIS models were trained using supervised learning based on the training dataset. During the training process, the model adjusted the parameters of the initial membership functions and improved the mapping between input indicators and output scores. A hybrid learning algorithm was applied to update the model parameters, combining backpropagation for premise parameters with the least squares estimator (LSE) for consequent

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parameters. This approach improves the learning efficiency and prediction capability of the ANFIS structure. The training process continued until the error reached an acceptable level. After 45 training epochs, the main ANFIS and sub-ANFIS models achieved satisfactory error performance. The calculated error values for the training, testing, and validation phases are reported in Table 2.

Table 2 Estimated Mean Square Error (MSE)

ANFIS Model	**Training Error $(\times 10^{-3})$**	**Testing Error $(\times 10^{-3})$**	**Validation Error $(\times 10^{-3})$**
Energy Policy	3.62	3.84	2.95
Institutional Stability	3.41	3.72	2.68
Governance Quality	1.86	2.34	1.29
Energy Security and Diplomacy	2.27	2.51	1.74
Crisis and Demand Management	3.08	3.46	2.21
Transparency and Corruption	0.284	0.319	0.247
Governance Sustainability	**2.18**	**2.63**	**1.47**

As shown in Table 2, all ANFIS models achieved low training, testing, and validation errors. The lowest errors were observed in the transparency and corruption sub-system due to its single-input structure. Overall, the results indicate acceptable learning accuracy and generalization performance of the proposed two-level ANFIS framework.

4.7 Model Validation and Testing

To evaluate the validity of the proposed model, the validation dataset was used to examine the generalization capability of the fuzzy inference system and to check the possibility of overfitting. The comparison between the actual and predicted values for the training and validation datasets showed a close alignment across the ANFIS structures. Figure 5 presents the agreement between the actual outputs and the predicted values of the main ANFIS model for the training dataset.

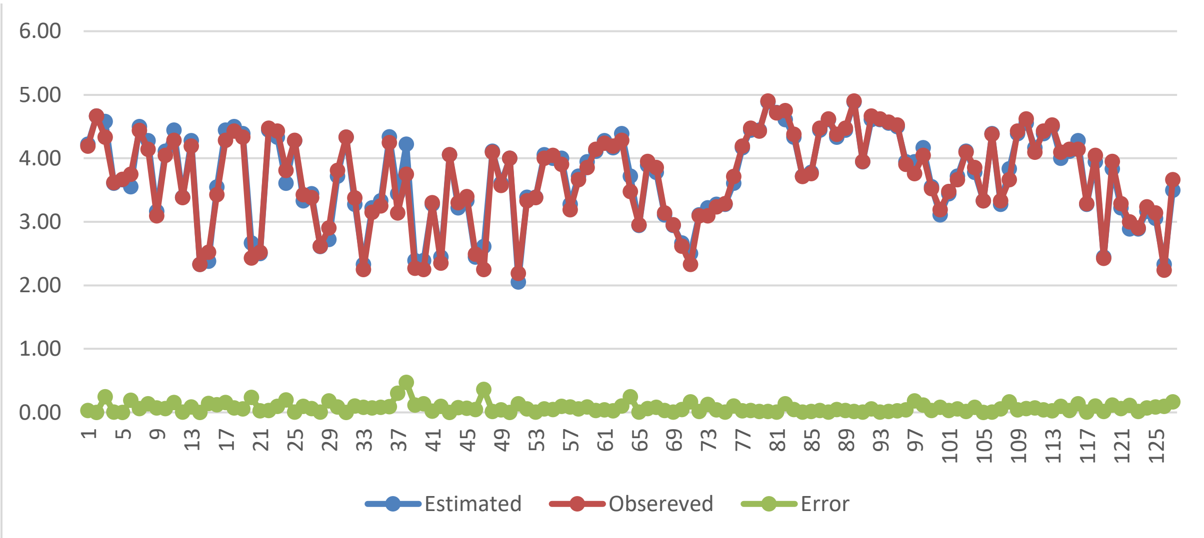

Fig. 5 Comparison between ANFIS output and training data

As shown in Figure 6, the average training error of the main ANFIS model was calculated as 0.00218, indicating an acceptable level of learning accuracy.

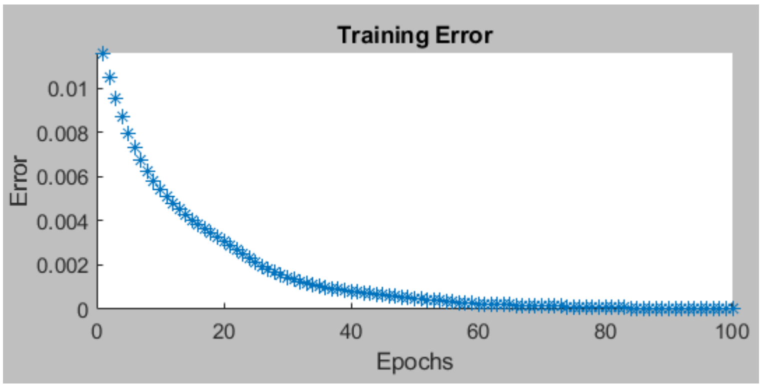

Fig. 6 Training error for ANFIS

The alignment of testing and validation data with the results of the ANFIS main system was confirmed accordingly. For these data, the calculated errors are 0.00263 and 0.00147, respectively.

Model validation and testing were implemented for all six sub ANFIS to optimize fuzzy rule weights and enhance model precision based on input relationships, and to make a better governance measurement metric.

In addition, a limit condition test was conducted to evaluate the behavioural validity of the model (Table 3). In this test, the designed Fuzzy Inference System (FIS) was examined under different extreme and intermediate input conditions, represented by the values 0, 0.5, and 1. Since all input variables were normalized within the range of 0 to 1, these values correspond to Very Low, Medium, and Very High levels, respectively. The results of the limit condition test indicate that the main FIS responds logically and consistently to variations in the input variables.

Table 3 Limit Condition Test for Main ANFIS

Type	Indicator	Value		
Inputs	Energy Policy	0	0.5	1
	Institutional Stability	0	0.5	1
	Governance Quality	0	0.5	1
	Energy Security and Diplomacy	0	0.5	1
	Crisis and Demand Management	0	0.5	1
	Transparency and Corruption	0	0.5	1
Output	Governance Sustainability	0.0144	0.492	1

For all six sub-ANFISs, this test was implemented, where they showed logical behavior.

4.8 Measuring Governance Indicators' Weights

After training the ANFIS models, the relative weights of the governance indicators were extracted based on the learned behavior of the system. These weights reflect the contribution of each indicator to the output of its corresponding sub-ANFIS model. In other words, indicators

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with higher weights have a stronger influence on the estimated governance sub-dimensional scores. The obtained weights were then normalized within each sub-dimension to support a clear comparison among the indicators. Table 4 presents the final weights of the governance indicators derived from the ANFIS-based evaluation process.

Table 4 Weights of Governance Indicator

Sub-Dimension	Weight	Indicator	Weight
Energy Policy	0.231	Energy Policies	0.0699
		Renewable Energy Development Policies	0.0508
		Subsidy Policies	0.0906
		Pricing Policies	0.1064
Governance Quality	0.135	Government Effectiveness	0.0539
		Regulatory Quality	0.0389
Institutional Stability	0.164	Political Stability	0.0702
		Economic Stability	0.0650
		Regulatory Predictability	0.0406
		Political Risk	0.0499
Energy Security and Diplomacy	0.182	Energy Security	0.0196
		Fuel Security	0.0230
		Network Security	0.0200
Crisis and Demand Management	0.196	Crisis Preparedness	0.0679
		Demand Management	0.0911
		Risk Management	0.0577
		Institutional Resilience	0.0528
Transparency and Corruption	0.092	Institutional Corruption	0.0316

The ANFIS-based results presented in Table 4 show the relative importance of governance indicators and governance sub-dimensions in assessing the sustainability of Iran's electricity energy management system. The weights of the indicators were estimated by comparing all indicators with each other, while the weights of the sub-dimensions were determined through a separate comparison among the governance sub-dimensions.

Figure 7 illustrates the relative weights of governance indicators to visualize a clearer comparison of indicator importance and highlights the most influential factors in governance sustainability.

At the sub-dimensional level, energy policy obtained the highest weight (0.231), indicating that policy-related factors have the strongest influence on governance sustainability. Crisis and demand management ranked second (0.196), followed by energy security and diplomacy (0.182), institutional stability (0.164), governance quality (0.135), and transparency and corruption (0.092). This ranking suggests that governance sustainability in Iran's electricity energy management system is primarily affected by policy design, crisis preparedness, demand-side control, and energy security considerations.

At the indicator level, pricing policies received the highest weight (0.1064), followed by demand management (0.0911), subsidy policies (0.0906), political stability (0.0702), energy policies (0.0699), crisis preparedness (0.0679), and economic stability (0.0650). These findings indicate that electricity pricing mechanisms, subsidy structures, demand management, and institutional stability are among the most influential factors in shaping governance sustainability. The high weight of pricing policies and subsidy policies reflects the importance of tariff structures, financial incentives, and consumption-control mechanisms in Iran's electricity sector.

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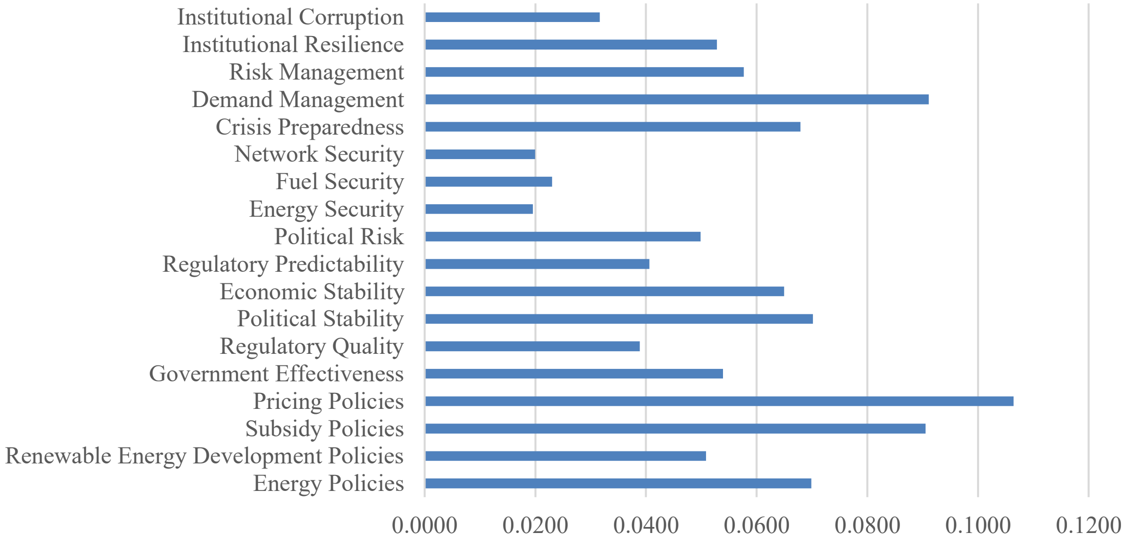

Fig. 7 Governance indicators diagram

Indicators such as energy security, fuel security, network security, and institutional corruption received lower relative weights at the indicator level. This does not mean that these factors are unimportant; rather, the trained ANFIS model estimated their relative contribution to be lower than policy-related, demand-side, and institutional indicators. Overall, the results emphasize that improving governance sustainability in Iran's electricity energy management system requires stronger attention to energy policy reform, pricing and subsidy adjustment, demand management, crisis preparedness, and institutional stability.

5 Discussion

The indicator-level results show that governance sustainability in Iran's electricity sector is influenced most strongly by pricing policies, demand management, subsidy policies, political stability, energy policies, crisis preparedness, and economic stability. This pattern indicates that the sector's sustainability depends not only on technical capacity but also on the interaction between policy instruments, consumption management, institutional stability, and crisis-response capability. More broadly, the findings support the view that Iran's energy imbalance cannot be interpreted solely as a supply–demand problem; it is also rooted in the governance arrangements through which prices, subsidies, investments, and crisis responses are designed and implemented. This interpretation is consistent with Faryadras et al. [12] and Pazuki et al. [5], who showed that Iran's recurring energy shortages arise from interconnected demand, subsidy, investment, infrastructure, and policy factors. However, the present study extends these studies by estimating the relative contribution of specific governance indicators and modelling their combined and nonlinear effects through ANFIS.

Pricing policy received the highest indicator weight, demonstrating the central role of tariff structures in the sustainability of electricity governance. Electricity prices affect consumption behaviour, peak demand, sectoral revenues, investment capacity, and incentives for energy efficiency. This finding is consistent with Aryanpur et al. [13], who showed that gradual and credible electricity-subsidy reform can reduce electricity demand and cumulative emissions while improving the conditions for renewable-energy development. The high importance assigned to subsidy policy reinforces this relationship, as poorly targeted subsidies can

[DOI: 10.71885/ijorlu-2026-4-737]

encourage inefficient consumption, weaken price signals, and reduce the financial resources available for infrastructure investment. Nevertheless, the significance of pricing and subsidy reform should not be interpreted as support for abrupt price increases. Their effectiveness depends on gradual implementation, transparent communication, targeted protection for vulnerable groups, and institutional credibility. Thus, pricing reform is simultaneously an economic, social, and governance intervention.

The strong contribution of demand management is also compatible with earlier studies of Iran's energy imbalance. Faryadras et al. [12] identified recurring electricity, natural-gas, and gasoline imbalances as interconnected consequences of growing demand and structural constraints, while Pazuki et al. [5] demonstrated that isolated supply-side measures are unlikely to eliminate electricity shortages over the long term. The present findings complement these studies by showing that demand management constitutes a governance capacity rather than merely a technical measure. Its effectiveness depends on appropriate incentives, reliable consumption data, public participation, interorganizational coordination, and the ability to implement peak-load and efficiency programmes. Accordingly, increasing generation capacity without strengthening demand-side governance may provide only temporary relief.

Energy policy and crisis preparedness also emerged as influential indicators. Their importance reflects the recurring and seasonal character of Iran's energy difficulties, including summer electricity deficits, winter gas shortages, fuel limitations, and network pressures. Previous research has mainly examined these challenges through scenario analysis and system-dynamics modelling [12,5]. In contrast, the present study evaluates the governance capacity required to anticipate disruptions, coordinate institutional responses, and adapt policies under crisis conditions. Crisis preparedness should therefore be understood as a structural component of sustainable governance rather than only as a short-term emergency response. Similarly, the importance of energy policy indicates that coherent and coordinated policy packages are required to align demand management, subsidy reform, infrastructure investment, and energy-transition objectives. This interpretation is consistent with Hafezi et al. [15], who emphasized the role of aligned reforms in supporting deeper decarbonization.

Political and economic stability also received relatively high weights, indicating that electricity governance is embedded in the broader institutional environment. Stable conditions can strengthen policy continuity, regulatory credibility, implementation capacity, and investor confidence, whereas instability may delay infrastructure projects, weaken long-term planning, and reduce the effectiveness of technically appropriate reforms. This result is consistent with Aghlimoghadam [14], who linked the limited development of renewable energy in Iran to institutional and credibility constraints. It also supports broader governance studies emphasizing the roles of coordination, legitimacy, and implementation capacity in policy effectiveness [6,7]. The findings therefore suggest that improvements in energy policy may have limited effects if they are not accompanied by a sufficiently stable institutional and economic environment.

By contrast, energy security, fuel security, network security, and institutional corruption received lower relative weights at the individual-indicator level. These results should not be interpreted as evidence that these indicators are unimportant. Instead, their lower weights indicate a smaller comparative contribution within the specific structure, expert sample, and crisis context examined in this study. Some of these indicators may also exert indirect or conditional effects through other governance dimensions. For example, transparency and institutional integrity may strengthen policy credibility, investment confidence, and public acceptance of tariff reform rather than producing an immediate independent effect on governance sustainability. This interpretation is compatible with Kamali et al. [9], who emphasized the contribution of transparency and traceability mechanisms to governance processes. Similarly, the lower individual weights of energy, fuel, and network security may reflect experts' stronger emphasis on the policy and institutional capacities through which

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security-related risks are managed. Therefore, the results represent a contextual prioritization rather than a general assessment of the intrinsic importance of these indicators.

The findings make three main contributions. Theoretically, the study conceptualizes governance sustainability as the outcome of interactions among policy, institutional stability, demand management, crisis preparedness, security, and transparency-related conditions, rather than as a simple additive combination of independent indicators. This perspective extends previous research that has treated governance as a single sustainability dimension or examined individual institutional factors separately. Methodologically, the study combines fuzzy Delphi-based indicator validation with a two-level ANFIS framework, allowing expert knowledge to be translated into an adaptive decision-support model capable of representing uncertainty, interdependence, and nonlinear relationships. This approach also extends conventional fixed-weight and linear aggregation methods by showing that the influence of one governance indicator may depend on the status of other indicators. Practically, the results provide policymakers with a prioritized basis for designing coordinated interventions focused on pricing and subsidy reform, demand-side management, crisis preparedness, and institutional stability. Hence, the study indicates that governance reform should be implemented as an integrated policy package rather than as a set of isolated measures.

6 Conclusion

This study developed an ANFIS-based framework for assessing governance sustainability in Iran's electricity energy management system. The findings demonstrate that sustainable electricity management depends on the combined influence of policy instruments, demand-side management, crisis preparedness, and institutional stability. In particular, effective pricing and subsidy policies are essential for improving consumption patterns, maintaining the financial viability of the electricity sector, and supporting long-term investment.

The results also indicate that technical and operational interventions alone cannot resolve the challenges facing Iran's electricity system. Their effectiveness depends on stable political and economic conditions, policy continuity, institutional coordination, and the capacity to anticipate and manage energy-related disruptions. Therefore, electricity-sector reforms should be implemented through coordinated policy packages rather than isolated measures.

The proposed framework contributes to the literature by capturing the nonlinear relationships among governance indicators and providing an adaptive decision-support tool for sustainability assessment. From a practical perspective, it can assist policymakers in identifying governance priorities and designing integrated strategies for pricing reform, subsidy adjustment, demand management, crisis preparedness, and institutional strengthening. Future studies could validate the framework in other regions, incorporate longitudinal data, and compare its performance with alternative intelligent modelling approaches.

The findings support practical policy scenarios centered on gradual electricity-pricing reform, targeted subsidy adjustment, demand-side management, crisis preparedness, and institutional strengthening. These measures should be implemented as coordinated policy packages and adapted to regional conditions rather than applied uniformly across the country.

Since the empirical data were collected from experts and respondents in Guilan Province, the findings should not be generalized uncritically to the entire Iranian electricity energy management system. Regional differences in electricity consumption, infrastructure, climate, institutional capacity, and policy implementation may influence governance priorities. Therefore, the findings represent a context-specific assessment, and further studies using larger and geographically diverse samples are required for national-level validation.

[DOI: 10.71885/ijorlu-2026-4-737]

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