Journal of
Renewable Energy Research and Applications (RERA)

Vol. 7, No 1, 2026, 79-97 *DOI: 10.22044/rera.2025.15943.1408*

Life cycle analysis and policy implications for Iran's wind energy innovation system: A co-evolutionary framework

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Received Date 17 March 2025; Revised Date 17 April 2025; Accepted Date 12 May 2025
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Abstract
This paper analyzes the life cycle of Iran's wind energy innovation system through a co-evolutionary framework that examines the interplay between the system and its contextual environment. Our analysis reveals that the system is transitioning from formation to growth, but remains vulnerable due to its high dependence on contextual factors. By examining three historical phases, we demonstrate how political, geographical, and sectoral contexts have critically influenced the system's development trajectory. The research identifies key systemic problems across functional, structural, and contextual dimensions, showing how their dynamics have either facilitated or hindered growth. Based on these findings, we propose policy recommendations focused on infrastructure stabilization, institutional support, and contextual management to overcome barriers and enhance the system's resilience and performance. This co-evolutionary perspective offers policymakers a novel framework for understanding and addressing the complex challenges facing renewable energy innovation systems.

Keywords: *Innovation System, Wind energy, Life cycle, Technological policy, Co-evolution of contextual factors*

1. Introduction

1.1. Background

In recent years, Iran's wind energy industry has made significant strides, driven by the country's efforts to diversify energy sources and reduce reliance on fossil fuels. Wind energy, with its high potential as a renewable resource, has gained the attention of policymakers, leading to the implementation of extensive programs to promote its development. A major focus has been on boosting research and development (R&D) activities aimed at improving wind energy technologies. The Iranian government has allocated substantial budgets, established research centers, and fostered collaboration between universities, research institutions, and the private sector to accelerate innovation in this field. Additionally, efforts have been made to promote the domestic production of wind energy components, reduce reliance on imports, and strengthen the local industry for wind turbines, control equipment, and other vital parts.

Government support through policies like wind energy purchase tariffs and financial incentives has encouraged investment and industry growth. These efforts have contributed to reducing Iran's dependence on traditional energy sources and advancing clean energy solutions by leveraging the country's local capabilities and natural resources. However, the development of the wind energy industry in Iran has encountered challenges and fluctuations, requiring ongoing analysis and strategic policymaking to ensure future progress.

1.2. Research gap and significance

Despite the growing importance of wind energy in Iran's energy portfolio, there has been limited systematic analysis of its innovation system from a life cycle perspective. Previous studies have primarily focused on technical aspects or economic feasibility without examining the complex interplay between the innovation system and its contextual environment. Additionally, while Technological Innovation System (TIS) frameworks have been applied to renewable energy sectors in developed economies, their application in countries with unique political, economic, and institutional environments like Iran remains underexplored.

Given the critical role of wind energy in reducing fossil fuel dependence and ensuring sustainable energy, there is a strong need to analyze and address the challenges faced by Iran's wind energy innovation system through a co-evolutionary lens [1]. This research contributes to both theoretical advancement by extending TIS frameworks to incorporate contextual dynamics and practical policy development by providing empirically-grounded recommendations for the Iranian context.

1.3. Research questions and paper structure

This research addresses three interrelated questions: (1) What is the current life cycle stage of Iran's wind energy innovation system, and what factors have shaped its development trajectory? (2) How do contextual factors co-evolve with the innovation system's structural and functional components across different development phases? and (3) What policy interventions would most effectively address the identified barriers and enhance the system's performance?

We hypothesize that the wind energy innovation system in Iran is transitioning from the formation to growth stage but remains highly dependent on contextual factors, making it vulnerable to external changes. We further hypothesize that the co-evolutionary dynamics between contextual elements and system components significantly influence whether the system experiences growth or decline in each development period.

The paper is structured as follows: after the introduction, the literature review covers transition studies, the Technological Innovation System (TIS), and its life cycle. The methodology section outlines research approaches, data collection, and analysis. The theoretical framework in the fourth section examines the evolution of the wind energy innovation system in Iran. Section five presents a conceptual model validated through structural-functional and dynamic assessments of TIS. Section six addresses the problems within Iran's wind energy innovation system, considering structural, functional, and contextual factors, while section seven explores the co-evolution of these contextual factors. The paper concludes with policy suggestions and key findings.

2. Literature review

2.1. Transition studies

Sustainable transition studies focus on major changes in sectors like energy, transportation, and food to achieve long-term sustainability [2]. These studies emphasize the interconnectedness of social, technical, institutional, and political changes, often highlighting phenomena like path dependence and lock-in [3]. Many scholars argue that existing sectors must undergo substantial transformations for sustainability [4]. Public policies are crucial in guiding these transitions, as seen in countries like Britain, Germany, and Canada, which have implemented strategies to phase out coal and nuclear power. The Technological Innovation System (TIS) approach aids in analyzing such transitions by considering technological, organizational, and institutional shifts, thus helping policymakers design effective interventions [5].

2.2. Technological innovation system

The TIS framework analyzes the emergence, development, and performance of new technologies, providing policy recommendations at the national level. It focuses on key elements: actors (e.g., manufacturers, research institutions, governments), institutions (both formal regulations and informal cultural norms), and networks (inter-organizational relationships for knowledge exchange). Grounded in evolutionary and systems theories, TIS highlights how interactions between system elements generate positive feedback, fostering technological development. The framework also incorporates broader contextual factors such as other innovation systems, sectoral structures, geographical influences, and political environments, which can significantly affect technology advancement [6-9].

Researchers can analyze TIS from either global or national perspectives. This approach helps identify systemic weaknesses and develop solutions that enhance technological development [10-12]. The framework categorizes actors based on their roles, such as civil sector entities, governments, NGOs, and academic institutions [13-15]. The interactions between these actors form essential networks that drive technological innovation [16-18]. TIS also examines critical system functions, including entrepreneurship, knowledge development and dissemination, market shaping, and legitimizing technologies [19-21]. The incorporation of contextual factors—historically overlooked—provides a more comprehensive understanding of technology development and the challenges it faces [8,22].

2.3. Life cycle of TIS

The Technology Life Cycle (TLC) literature focuses on the stages through which technologies emerge and mature, shaped by technical, economic, social, political, and organizational processes [23]. The TLC is typically divided into the stimulation phase (high uncertainty and competition among technologies), the emergence of a dominant design, and gradual changes as the technology matures [24,25]. It also distinguishes between gradual and discontinuous innovations, which influence technology dynamics and socio-political factors [26-29]. Markard identifies three main blocks for analyzing the TIS life cycle:

a) TIS and Contextual Factors: Analyze the relationship between TIS and its broader context [2].
b) Analytical Dimensions: Examines system size, leading players, institutional structure, and technology diversification [30,31].
c) Evolutionary Perspective: Focuses on changes in system expansion, efficiency, and technology development paths [2].

Marquardt stresses the importance of contextual changes, arguing that technologies may evolve from niche applications to broader uses as policies shift, and further refinement of TIS life cycle conceptualizations is needed [2]. The TIS life cycle is often divided into four stages:

- Formation: characterized by few actors, low sales, and heavy government funding, with limited interaction between the system and its context [29,32-34].
- Growth: Marked by rapid expansion, increasing sales, and emerging formal institutions like safety standards, with stronger relationships among producers, suppliers, and markets [35,36].
- Maturity: Features stable markets, high institutionalization, and incremental technological development [9].
- Decline: Sales drop, actors exit, and systems face instability, with the breakdown of intermediaries and value chains [4,37].

The transition between stages is often gradual, and not all TIS systems follow a linear path. Some may face challenges in the growth stage or instability after reaching maturity [9,38-41]. Additionally, a TIS may undergo these stages while being part of a larger social and technological transition [42].

While the TIS framework has been widely applied to analyze renewable energy transitions in developed economies [38,41], significant gaps remain in understanding how innovation systems evolve in developing country contexts with unique political, economic, and institutional environments [8]. Particularly lacking is research examining the co-evolutionary dynamics between contextual factors and innovation systems in countries with state-centric energy sectors and complex geopolitical challenges. Iran's wind energy sector presents a compelling case study that has been underexplored in the literature. Previous studies have primarily focused on technical or economic aspects of renewable energy in Iran, but have not examined the complex interplay between the innovation system and its contextual environment from a life cycle perspective. This research addresses these gaps by: (1) developing a novel co-evolutionary framework that systematically analyzes the bidirectional influences between innovation system components and contextual factors; (2) providing one of the first longitudinal analyses of an emerging renewable energy TIS in Iran across multiple development phases; and (3) offering empirically-grounded policy recommendations that account for the unique challenges faced by countries with similar institutional and political contexts. By integrating theories of co-evolution with the TIS framework, this study contributes to both theoretical advancements in transition studies and practical knowledge for policymakers in developing economies.

While these theoretical frameworks provide valuable analytical tools, their applicability to Iran's wind energy innovation system requires critical examination. The TIS framework, developed primarily in Western contexts, assumes a degree of market liberalization and institutional transparency that may not fully align with Iran's state-centric energy governance structure. Carlsson and Stankiewicz's original conceptualization [10] emphasizes network formation among diverse actors, yet Iran's hierarchical decision-making processes potentially constrain such horizontal relationships. Similarly, the life cycle stages proposed by Markard [2] presume market-driven transitions between phases, whereas Iran's development trajectory has been significantly influenced by non-market factors such as geopolitical tensions and state priorities. Furthermore, transition studies' emphasis on destabilizing incumbent regimes [3] must be reconsidered in contexts where fossil fuel systems are deeply embedded in national economic and political structures. This research therefore adapts these frameworks by placing greater emphasis on contextual dynamics and power relations, incorporating insights from development studies that account for institutional asymmetries and center-periphery knowledge transfers. By critically integrating these theoretical perspectives rather than applying them wholesale, this study develops an analytical approach better suited to understanding innovation system dynamics in non-Western, state-influenced energy transitions.

3. Methodology

3.1. General approach and type of research

This applied research focuses on Iran's wind power plant sector and examines the life cycle of the Technology Innovation System (TIS) in this field. The study aims to determine the current stage of the technological life cycle of the wind energy TIS and explore the relationship between the evolution of contextual factors and this innovation system. The research employs content analysis, document review, and semi-structured interviews, utilizing a mixed-methods approach to gather data from various sources and ensure reliable results [43]. Figure 1 illustrates the steps of this research. As shown in figure 1, our research methodology followed a systematic seven-step process. We began by extracting key parameters from the literature to position Iran's wind energy system within the technology life cycle framework (Step 1). This foundation informed the development of our conceptual model based on established TIS analysis methods (Step 2), which was subsequently validated through focus group meetings with industry experts (Step 3). The research then progressed to a historical analysis of the system's evolution and life cycle positioning (Step 4), followed by an examination of system dynamics in relation to changing contextual factors (Step 5). The final analytical phase involved classifying and summarizing the identified issues and problems (Step 6), which led to the determination of policy goals and recommendations with expert consensus (Step 7). This structured approach ensures a comprehensive analysis that moves from theoretical framing to practical policy implications, while integrating both expert knowledge and empirical evidence throughout the process.

Our mixed-methods approach systematically integrated qualitative and quantitative elements throughout the research process. Quantitatively, we collected and analyzed numerical data on installed wind capacity, investment trends, number of actors, and technology sales volumes across the three identified historical periods. These metrics were essential for objectively positioning Iran's wind energy system within the TIS life cycle framework. Qualitatively, we conducted semi-structured interviews and focus groups with industry experts, analyzed policy documents, and evaluated institutional structures to understand the contextual factors and their co-evolutionary dynamics. The integration occurred primarily at the analytical phase (Steps 5-6), where quantitative indicators were triangulated with qualitative insights to validate our findings regarding system positioning and to identify causal relationships between contextual factors and system development. This integration was further strengthened during the expert validation process (Step 7), where preliminary findings were presented to industry stakeholders who helped refine the interpretation of both data types, ensuring that our conclusions accurately reflected the complex realities of Iran's wind energy innovation system.

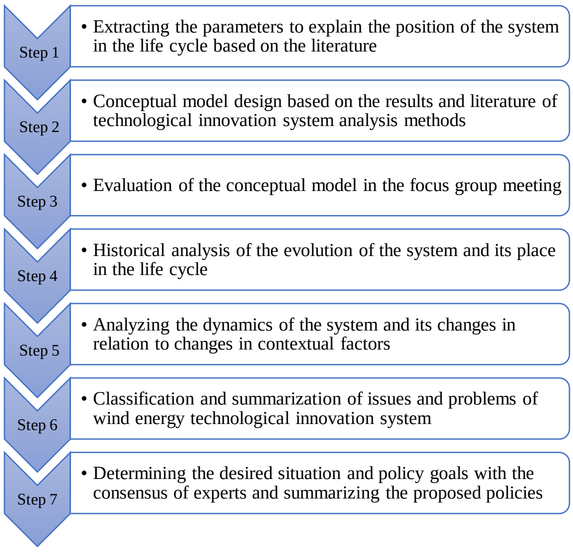

Figure 1. The systematic seven-step research methodology employed in this study

3.2. Data collection methods

In this research, data collection was conducted using a synthesis method, which included three primary sources: interviews, observations, and document study. To ensure data accuracy, specialized sampling and snowball methods were used to select interviewees. Seven wind energy experts were chosen, and they participated in various stages of the research, including focus group meetings. Additionally, policy documents about renewable energy were analyzed through library searches and expert interviews. Table 1 provides details of the individuals interviewed at different stages and in the focus group meetings.

Table 1. Expert participants interviewed during research, including their organizational positions and interview dates.

Organizational position	Interview date
Head of Renewable Energy and Electricity Efficiency Organization (SATBA)	3 - 9 - 2022
Vice President of SATBA Renewable Energy	21 - 9 - 2022
Senior expert in SATBA wind energy	6 - 9 - 2022
Advisor to the president and former vice president of SATBA planning	12 - 10 - 2022
Secretary of Renewable Energy Association (Chamber of Commerce)	16 - 10 - 2022
CEO of Mapna Industrial Group Renewable Energy Company (Wind Turbine Manufacturing)	8 - 10 - 2022
Advisor to the Minister of Energy and former head of SATBA	2 - 10 - 2022

3.3. Data analysis methods

The comparative content analysis method was employed for data analysis in this research. This approach was used to test and verify the validity of theories, models, or assumptions regarding the status of wind energy life cycle indicators in Iran. The content analysis process involved specific sampling stages, data collection, and analysis. It can lead to the development of a model or conceptual framework, summarize data, draw inferences, and formulate theories. The method ensures precision in research design, objectivity, validity, reliability, and generalizability. Key policy documents approved by the country's upstream institutions that address renewable energy were analyzed through library searches and expert interviews. These documents include the wind energy strategic document, technology development document, wind turbine industry documents, wind turbine site handover documents, project control documents, contracts for wind turbine installation, knowledge-based production leap law, people's government transformation document, and the renewable energy operational plan charter.

Despite our rigorous methodological approach, we acknowledge several limitations in our data collection process that may affect the interpretation of results. First, the relatively small sample of expert interviews (n=7), while representing key stakeholders across the sector, may not capture all perspectives, particularly those from smaller private firms or international actors. Second, our snowball sampling method, while effective for identifying knowledgeable participants, could have introduced selection bias by limiting representation to experts within certain professional networks. Third, the document analysis may have been affected by availability bias, as we primarily accessed documents provided by established institutions, potentially underrepresenting critical or alternative viewpoints. Additionally, the semi-structured interview format, while allowing for deeper exploration of topics, may have introduced interviewer effects where participants responded in ways they perceived as desirable. Finally, the study's focus on formal institutions may have overlooked informal institutional factors that influence the wind energy innovation system. We have attempted to mitigate these limitations through methodological triangulation and validation of findings with experts, but these constraints should be considered when interpreting the results.

4. Theoretical framework and life cycle parameters

4.1. Reviewing the concept of the innovation system life cycle

The life cycle of the Technology Innovation System (TIS) examines the development, maturity, and decline of technology over time. Markard has identified three main blocks to analyze this life cycle, emphasizing that exploring these blocks can improve the understanding of the TIS's life cycle and its interaction with contextual factors [2].

a) TIS and Contextual Factors: This block focuses on the interactions between the innovation system and its external environment, including economic, political, and social factors that influence innovation.
b) Analytical Dimensions: This section includes three key elements:
   - “System size and main actors," which looks at the number of activities and the participation of key actors in the innovation system.
   - “Institutional structure," which explores the system's structure, the institutions within it, and the relationships between them.
   - “Technological diversity and performance," which examines technological growth, development, efficiency improvements, and the emergence of dominant technologies.
c) Evolutionary Perspective: This block analyzes the evolution of the TIS and

contextual factors over time, focusing on changes in expansion, decline, productivity, and the development path of technology.

4.2. Explanation of parameters of evolution in wind energy innovation system

To analyze the life cycle of the Technology Innovation System (TIS), three key dimensions are considered:

a) Expansion and Decline: This dimension tracks changes in the size and activities of the innovation system. Expansion occurs with the entry of new players and increased research and development, while decline is marked by the exit of players and shrinking markets.

b) Institutionalization and Instability: Institutionalization refers to the formalization and coherence of institutional and inter-organizational structures, often leading to reduced technological diversity [2]. Instability, on the other hand, is associated with the breakdown of these structures due to institutional frictions and changes in contextual factors.

c) Performance and Direction of Technology Development: This dimension focuses on changes in technology performance, which can improve gradually or rapidly. The direction of technological development may shift in response to contextual factors or the emergence of complementary technologies. For example, a technology initially developed for a specific application may later be adapted for broader purposes, contributing to the creation of an innovation system.

The evolution of the innovation system depends heavily on its interactions with contextual factors. Political changes, economic conditions, and developments in complementary technologies can all significantly influence the system's trajectory. These interactions may be one-way or two-way, as seen in the case of the rapid development of biogas technology impacting the agricultural sector in Germany [2]. These processes are interdependent, where system expansion can lead to institutionalization and influence the direction of technology development. Additionally, changes in contextual structures can affect other aspects of the TIS. Table 2 summarizes the key parameters used for life cycle analysis, including system size, network structure, technological efficiency, and contextual interactions. These parameters are assessed using both quantitative and qualitative methods, relying on documentary and interview-based analyses.

4.3. Determining the life cycle of the TIS of wind energy in Iran

An examination of Iran's wind energy innovation system using specific criteria and sub-criteria reveals that the system is in the growth stage. The analysis, conducted through expert meetings and document reviews, led to the following findings:

a) Size of the System and Players: The system is in the growth stage, characterized by an increase in the number of players, growth in technology sales, and reduced vertical integration due to production concentration in a few domestic companies.

b) Networks and Institutional Structure: The institutional structure and coordination are growing, with active institutions gaining more recognition. However, institutional complexity has not significantly increased, indicating the system remains in the growth stage.

c) Efficiency and Diversity of Technology: The system is entering the growth stage in this dimension as well. While performance criteria have not been defined and no dominant plan has emerged, the reduction in technological diversity and concentration of production in two domestic companies reflect the characteristics of this stage.

d) Communication with Contextual Factors: The system's interaction with contextual factors is still in the formation stage. The strong, one-sided influence of these factors on the system suggests that any change in the context could directly impact the system's development path.

Overall, Iran's wind energy innovation system is poised to continue its growth, but this requires strengthening and stabilizing the current trends.

Table 2. Life cycle analysis parameters used to position Iran's wind energy innovation system within the TIS framework.

Row	Life cycle determination parameter	benchmark (index)	Measurement status (quantitative-qualitative-combination)	Research method (interview analysis/document analysis)
1	**The size of the system and the actors**	The amount of technology sales	Quantitative	Documentary analysis
		Technology sales growth	Quantitative	Documentary analysis
		Number of actors	Quantitative	Documentary analysis
		The degree of vertical integration	Qualitative	Interview analysis
2	**The state of networks and the institutional structure of the system**	The degree of structure of the network	Qualitative	Interview analysis
		Formality and complexity of institutional structure	Qualitative	Interview analysis
3	**Efficiency and diversity of system technology**	Technology performance level	Qualitative	Interview analysis
		Degree of technological diversity	Qualitative	Interview analysis
4	**The state of the interaction of contextual factors with the system**	Intensity and mode of influence of technological innovation context and system	Qualitative	Interview analysis
		The degree of dependence	Qualitative	Interview analysis

5. Compilation and validation of conceptual model

This section examines the impact of the Technology Life Cycle (TLC) on the wind energy innovation system, using the industry and TLC frameworks to analyze technological emergence and maturity. The industry life cycle focuses on firm dynamics, such as entry, exit, and market size [2], while the TLC highlights patterns of technology emergence, dominant design, and penetration. Effective policymaking must consider both the emergence of new technologies and the phase-out of outdated ones, such as coal technologies and energy-consuming lamps. The TLC framework is applied to analyze Iran’s wind energy innovation system, incorporating expert opinions on critical system development parameters.

5.1. Analysis of different generations of TIS

5.1.1. Analysis-based on system output

This analysis focuses on system performance, often using outputs like technology release or carbon dioxide reduction in the energy sector. However, output indicators may not accurately reflect early-stage system performance [44]. As technology develops, these outputs become key criteria for evaluation.

5.1.2. Analysis-based on structural factors of the system

Early analyses of TIS focused on structural components, assuming that system outputs are influenced by interactions between these components. This perspective was expanded in the 1990s to include products, industries, and sectors. Marquardt and Truffer emphasized the role of actors and their strategies in influencing system outputs [45], while Truffer et al. explored the impact of rules and norms on performance [46]. Other studies highlighted the role of inter-organizational networks in enabling collective resource development [47, 48].

5.1.3. Structural-functional analysis

This combined approach examines the mutual effects of structural components and system functions. The approach emphasizes that appropriate structures are essential for achieving desired outcomes and proposes solutions to identified structural issues. The analysis includes mapping system components, evaluating function status, allocating performance points, identifying system problems, and designing policy proposals. This method provides a comprehensive understanding of system issues and offers detailed policy recommendations [46,49].

5.2. Dynamic analysis of TIS and driving engines

Driving engines play a crucial role in the development and stabilization of the TIS across different stages of the Technology Life Cycle (TLC):

- Science and Technology Engine: Focuses on knowledge development and research, essential in the early stages of technology development. It supports functions such as knowledge dissemination, resource mobilization, and entrepreneurial activities.
- Entrepreneurship Engine: Supports commercialization and reduces technological uncertainties, strengthening entrepreneurial efforts and reducing reliance on government support.
- Structuring Engine: Advances technology by integrating scattered activities and maturing them into a product, activating all system functions, particularly market shaping and creating formal structures.
- Market-Driving Engine: Once the TIS reaches maturity, this engine drives technology through market competition, creating demand, and setting rules that solidify the technology in existing systems.

These engines work together to stabilize and develop the TIS at different stages of the TLC.

5.3. Analysis output, system problems

The analysis of TIS has often identified systemic problems without categorizing them comprehensively. Many studies have focused on intra-systemic issues, neglecting environmental and social factors, especially in developing countries. This paper addresses this gap by exploring additional systemic problems and their effects on TIS's structural and functional aspects. Problems that delay development, such as institutional and infrastructural issues, are categorized based on actor networks, markets, and institutions [13,50-52]. Environmental factors, as Carlson noted, also play a significant role in shaping TIS performance and should be considered in analyses [53].

5.4. Explaining the conceptual model of research

TIS analyses have shifted from static structural models to dynamic approaches that incorporate changes over time. However, two key gaps remain: (1) the lack of dynamic analysis of structural and contextual factors and (2) the insufficient examination of how contextual factors evolve. This research proposes a conceptual model that addresses these gaps, incorporating the dynamics of structural and contextual factors and their effects on system functions. The model identifies and classifies seven types of system problems, with further exploration provided in subsequent sections. Figure 2 illustrates our novel conceptual model of the wind energy innovation system, which visualizes the hierarchical and interdependent relationships between three critical layers: contextual factors (left), structural elements (middle), and functional components (right). Each layer contains its own set of elements that interact both within their respective layer and across layers through the co-evolutionary pathways indicated by red arrows.

The contextual layer (pink) includes four key underlying factors: political, geographical, electricity industry, and other innovation systems (particularly fossil fuels). These external forces create pressures that cascade through the structural layer (blue), which consists of actors, interactions, institutions, and infrastructures. These structural elements, in turn, shape the system's seven core functions (green): entrepreneurship, knowledge development, knowledge dissemination, legitimacy, market formation, resource provision, and system orientation.

This model extends traditional TIS frameworks by explicitly mapping the mechanisms through which contextual factors influence system development. The red arrows represent the dynamic pathways of influence, showing how changes in one layer propagate through the system. For example, political factors like sanctions may affect infrastructure availability, which subsequently impacts entrepreneurial activities. This visualization helps explain why Iran's wind energy innovation system has experienced periods of growth and stagnation corresponding to changes in these cross-cutting relationships. By capturing these multi-level dynamics, the model provides a more comprehensive framework for analyzing system problems and developing targeted policy interventions.

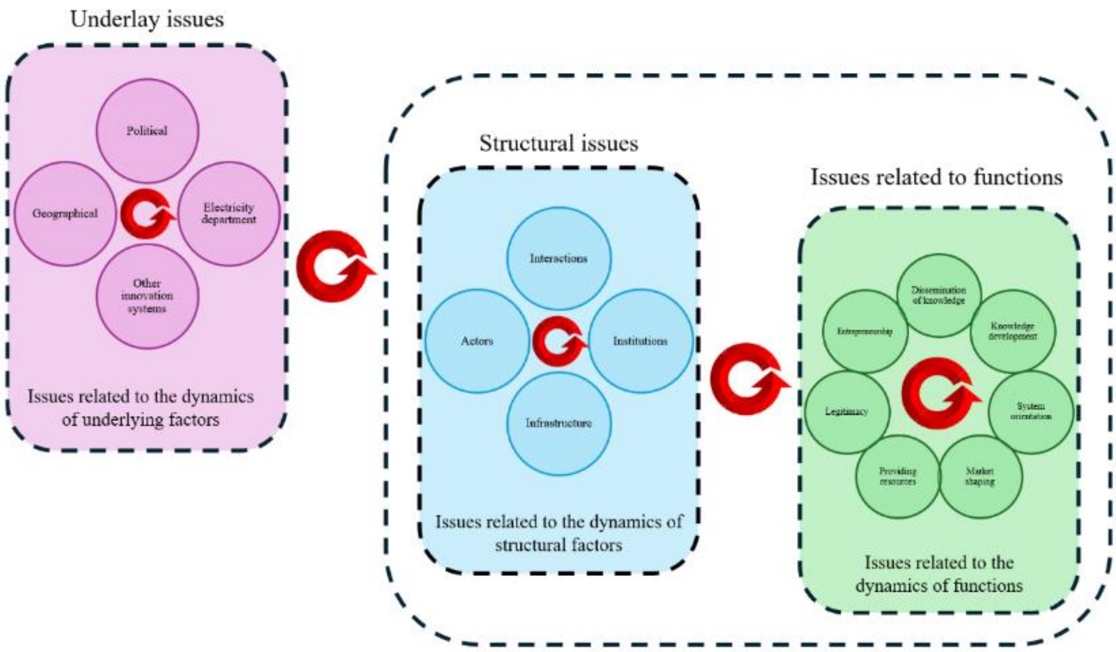

Figure 2. Conceptual model illustrating the co-evolutionary dynamics between contextual factors, structural elements, and functional components of Iran's wind energy innovation system

6. Analysis of problems and failures of wind energy innovation system in Iran

Before proceeding with our detailed analysis, it is important to clarify several key technical concepts that will be used throughout this section. A 'technological innovation system' (TIS) refers to the network of actors, institutions, and technologies that collectively develop and diffuse new technologies. 'Functional components' represent the processes that contribute to technology development, such as knowledge creation and entrepreneurial activities. 'Structural elements' include the tangible organizations, networks, and infrastructure that enable these functions. 'Contextual factors' are external influences like political systems or geographical conditions that shape the innovation environment but are not directly part of it. When we discuss 'co-evolution,' we are referring to the mutual influence and adaptation between these different elements over time. By examining the system through these lenses, we can identify specific barriers and opportunities for wind energy development that might otherwise remain obscured by more conventional sectoral analyses. This section presents the research model and analyzes the critical problems hindering the development of Iran's wind energy innovation system. The problems are categorized into three main types: functional, structural, and background. The analysis also considers the dynamics and changes of each problem over time. The discussion begins with an examination of the functional problems and their evolution across three time periods, followed by the analysis of structural problems and, finally, background issues. The section concludes by evaluating the dynamic effects of each problem on other layers of the system.

6.1. Structural issues and functions of the innovation system

6.1.1. Various functions

This section analyzes the critical functions of Iran's wind energy innovation system over three periods to understand how each function contributed to the system's growth and sustainability. The following functions are examined:

a) Entrepreneurial Function: This function plays a significant role in developing wind power plants but has faced fluctuations. Initially, wind farm construction started, but attention was mainly on fossil fuel power generation. In the second period, entrepreneurial activities declined due to economic challenges and an unsuitable market. However, with financial conditions improving in the third period, this function grew again, as evidenced by the growth in wind power plant capacity between 2017 and 2018.

b) Knowledge Development and Dissemination: This function remained stable across the three periods. While knowledge about wind turbine manufacturing was introduced, access to advanced technologies was limited by high costs, resulting in little change in the development and dissemination of knowledge.

c) System Direction Function: Initially, this function was underdeveloped. It grew in the second period with the introduction of guaranteed purchase regulations for wind power but declined due to frequent rule changes. In the third period, the removal of pricing barriers led to significant improvement.

d) Market Shaping Function: In the first period, this function emerged with the establishment of turbine production factories and power plants. It expanded in the second period through the introduction of guaranteed purchase laws but faced a decline due to financial problems. In the third period, the market grew again as economic justification for wind power improved.

e) Resource Provision Function: This function remained weak throughout all three periods. In the first period, resources were mainly government-funded and limited. In the second period, private sector investments were made but ceased due to unmet demands. In the third period, with slight improvements in investment, this function showed some progress.

f) Legitimizing Function: This function faced challenges in the first two periods due to competition from gas electricity and low fuel prices. However, in the third period, legal changes in fuel pricing improved the legitimacy of wind power.

These analyses illustrate how each function's development influenced the overall progress of Iran's wind energy innovation system over time. Figure 3 illustrates the evolution of installed wind power capacity in Iran from 1387 (2008) to 1401 (2022), providing empirical evidence that directly corresponds to the three developmental periods identified in our analysis. The first period (1387-1391) shows modest but steady growth from 0.65 MW to 16.17 MW, reflecting the formation stage characterized by limited actors and heavy government involvement. The second period exhibits a fluctuating pattern with notable expansion between 1391-1392 (16.17 MW to 28.35 MW) and 1395-1397 (29.98 MW to 45.28 MW), followed by significant decline in 1398 (14.25 MW). This volatility aligns with our findings regarding the impact of privatization laws, guaranteed purchase regulations, and subsequent infrastructure challenges.

The third period demonstrates the most dramatic changes, with capacity reaching its peak in 1399 (2020) at 63.85 MW—more than quadruple the 1391 value—before declining to 37.19 MW by 1401. This pattern empirically validates our analysis of how policy shifts, changing attitudes toward renewable energy, and persistent infrastructure challenges affected the system's growth trajectory. The decline after 1399 particularly illustrates the continued vulnerability of the system to contextual factors despite improvements in institutional coordination and market formation.

The overall trend confirms our conclusion that Iran's wind energy innovation system remains in transition between the formation and growth stages, with its development significantly influenced by the co-evolutionary dynamics between contextual factors and system components. The capacity fluctuations provide clear evidence of how political, infrastructural, and economic factors have created periods of both advancement and regression in the development trajectory.

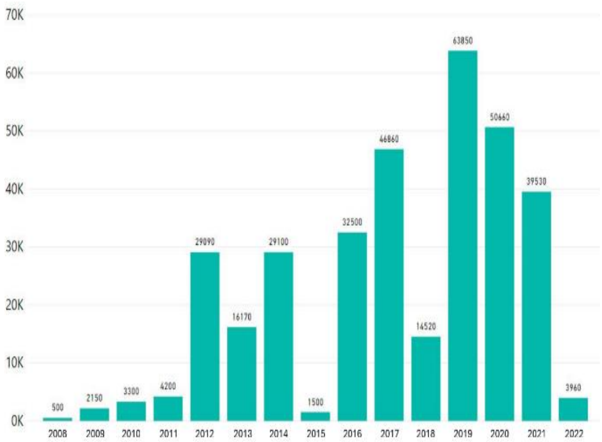

Figure 3. Evolution of installed wind power capacity in Iran from 1387 (2008) to 1401 (2022), measured in kilowatts

6.1.2. Issues related to actors, interactions, institutions, and infrastructure

The structure of Iran's wind energy innovation system has evolved over three periods, shaped by actors, interactions, institutions, and infrastructures. Each factor has contributed to the system's development or posed challenges at different stages:

a) Actors: The role and number of actors in the system have changed significantly. In the first period, the Atomic Energy Organization played a central role. The second period saw the formation of SATBA and the growing involvement of TAVANIR, which led to an increase in turbine manufacturers and power plant construction companies. In the third period, large national companies entered the industry, leading to a shift in the actor landscape and steady growth in the ecosystem.

b) Interactions: Analyzing interactions has been challenging due to their complexity and a lack of information. A key feature, however, has been the gradual growth of the private sector. This sector's involvement in wind energy expanded during the second period, declined in the early 1990s, and has grown again since, following a pattern of gradual growth, decline, and resurgence.

c) Institutions: The institutional landscape has seen continuous growth. New laws were introduced in each period, and structural barriers were removed, which strengthened the innovation system. The second period marked a significant increase in regulations, and the third period saw further institutional development, contributing to ongoing institutionalization.

d) Infrastructures: Infrastructure development evolved across periods. During the first period, it focused primarily on knowledge generation, including the creation of a national wind map. The second period saw financial infrastructure emerge through electricity bill fees designated for renewable development. However, economic sanctions severely reduced foreign exchange availability, which weakened the financial foundation of the system. By the third period, some of these challenges were alleviated, though infrastructure issues remain, particularly the inadequacy of the electricity grid for wind power plants, which has yet to be resolved.

These four factors—actors, interactions, institutions, and infrastructures—have all shaped the wind energy innovation system in Iran, with progress and challenges at each stage of its development.

6.2. Contextual issues (political, geographical factors, and the impact of other innovation systems)

This section analyzes the factors that have directly or indirectly influenced the development of Iran's wind energy innovation system, highlighting political, geographical, and cross-system factors.

a) Political Factors: Sanctions have been a continuous challenge, particularly in the 1990s when they escalated, increasing investment risks during the second period. Additionally, the approval of the Law on Implementing Article 44 of the Constitution during the second period caused significant changes in the innovation system's components.

b) Geographical Factors: Iran’s geography has significantly influenced wind energy development. Key factors include the distance between windy areas and consumption centers, Iran's favorable location for wind power generation, and the high cost of electricity transmission. These geographical characteristics have created stable conditions for the wind power industry over time.

c) Impact of Other TIS: The gas innovation system has had a substantial effect on the wind energy sector. In the first period, the rapid growth of the gas sector, especially due to developments like the South Pars gas field, made the electricity industry increasingly reliant on gas electricity. This trend continued into the second period. However, in the third period, with a decline in gas production, the gas innovation system also decreased in influence, affecting the wind energy sector's dynamics.

d) Electricity Industry: Wind power competes directly with thermal power, which relies heavily on gas production and consumption. Fluctuations in gas production have had a direct impact on the electricity industry, including wind power, leading to varying conditions for the sector during different periods.

6.3. Analysis of the dynamics of functions and factors in different periods

6.3.1. Dynamic analysis of system functions

The development of Iran's wind energy innovation system can be divided into three periods, each marked by different dynamics in key functions.

a) First Period (Formation of the Innovation System): The primary focus was on knowledge development, entrepreneurship, and knowledge dissemination. These functions positively impacted the entrepreneurial sector, leading to the formation of turbine manufacturing and wind power plant installation companies. Functions like system orientation, resource provision, and legitimation were in their initial stages, and market shaping was just beginning to take form. Overall, the emphasis was on knowledge development, which gradually led to the emergence of a market and entrepreneurial activities.

b) Second Period (Implementation of the Privatization Law): During this period, system direction became more prominent due to new regulations on wind power production and sales. However, the functions of entrepreneurship, knowledge development, and knowledge dissemination declined due to reduced private investment and research activities. The market-shaping function continued to grow due to the adoption of new laws, but resource provision challenges hindered the sustainable realization of other functions. The lack of resources negatively affected entrepreneurship and legitimization, dampening investor motivation.

c) Third Period (Relative Improvement and New Laws): In this period, functions like legitimization and market shaping improved due to new regulations. System direction continued to play an important role in realizing other functions. While resource provision challenges decreased compared to the previous period, it was still not fully realized, though there was a positive outlook for future resource supply. Despite some improvements in the third period, resource provision challenges remain ongoing.

6.3.2. Dynamic analysis of structural factors

The development of Iran's wind energy innovation system can be divided into three periods, each marked by the evolution of key structural factors such as actors, interactions, and infrastructure.

a) First Period (Formation of Actors): This period saw the formation of key actors, including the Atomic Energy Organization and the New Energy Organization of Iran, which played a vital role in the early stages. Entrepreneurs and wind turbine manufacturers also gradually entered the field. However, the technical and legal infrastructures were not fully developed, limiting the interactions between actors and slowing the system's growth. Overall, this period was focused on the initial formation of actors, but infrastructure limitations hindered development.

b) Second Period (Growth and Decline): The second period experienced two phases: an initial growth phase followed by a decline. Growth occurred with the entry of investors and new producers, supported by protective laws like the guaranteed purchase of electricity. However, by the end of the period, infrastructure issues—both technical and financial—caused a withdrawal of investors, leading to a cessation of growth. The lack of coordination in infrastructure and reduced government payments were major factors that negatively affected the system's development.

c) Third Period (Coordinated Institutions and Infrastructure Challenges): In this period, institutions and laws became more coherent, and greater coordination among rules and regulations led to stronger interactions and an increase in the number of actors. However, technical and financial infrastructure issues remained, particularly with the integration of wind power into the national grid. While institutions and laws matured, infrastructure challenges continued to hinder the system's growth.

6.3.3. Dynamic analysis of contextual factors

The development of Iran's wind energy innovation system was influenced by geographical, political, and fossil fuel system factors over three periods:

a) First Period (Initial Development): Geographical factors, such as Iran's favorable location for wind energy, provided initial conditions for research and development in wind power. However, the long distance of windy areas from the power grid and their lack of development negatively affected growth. The fossil fuel innovation system, with cheap and readily available resources, limited the expansion of wind energy. Political factors, such as sanctions and legal instability, further strengthened the fossil fuel system and hindered the wind power sector.

b) Second Period (Political Challenges): The influence of political factors intensified, especially with the implementation of Article 44 of the Constitution and changes to subsidies. The JCPOA and the subsequent U.S. withdrawal caused political instability and reduced foreign exchange resources. Although laws such as the guaranteed purchase of wind power were approved, their effectiveness was undermined by low electricity prices and political fluctuations. Geographical factors remained favorable, but the negative impact of political factors interrupted wind energy development during this period.

c) Third Period (Improvement in Conditions): Political factors continued to affect wind energy, but the influence of the fossil fuel system decreased due to gas shortages and economic problems. This allowed the geographical advantages for wind energy to become more prominent. As fossil fuel use decreased and favorable geographic conditions for wind power re-emerged, wind energy development improved during this period.

7. Explanation of co-evolution of contextual factors and wind energy innovation system

In the development of Iran's wind energy innovation system, several factors influenced its evolution over three periods:

a) First Period (Formation of the System): Geographical factors, particularly Iran's favorable wind conditions, played a crucial role in the development of knowledge and the formation of key actors in wind energy. However, the dominance of the fossil fuel system and inadequate infrastructure hindered the industry's overall growth. Sanctions, as a political factor, imposed restrictions on actor activities. Despite these challenges, the positive influence of geographical factors was evident in the early stages of wind energy development.

b) Second period (Political and infrastructure challenges): Political factors became more significant during this period. International sanctions and domestic political volatility created instability. While guaranteed purchase laws initially attracted investors to wind power, the combination of inadequate infrastructure and political uncertainty ultimately discouraged participation. This led to reduced motivation among key actors and stagnation in the development process. This period was marked by unstable co-evolution, with limited infrastructure and political obstacles.

c) Third Period (Policy Shifts and Improvement): Policymakers' changing attitudes towards renewable energy led to improved co-evolution between contextual, structural, and functional factors. This shift strengthened actors and institutions, facilitating market development and entrepreneurship. The decline in gas production and challenges faced by thermal power plants transformed the fossil fuel system from a deterrent to an enabling force for wind power. While infrastructural and financial challenges persisted, new policies led to a positive trend in the growth of the wind energy innovation system.

To strengthen the empirical foundation of our analysis, we will enhance the discussion of policy impacts by establishing clearer links between specific interventions and their measurable outcomes. Figure 3 provides empirical evidence of capacity fluctuations that correspond to policy changes across the three periods, but additional quantitative metrics would better illuminate these relationships. The paper currently shows that guaranteed purchase laws in the second period initially stimulated growth, followed by a decline when implementation faltered, and then demonstrates how policy shifts in the third period led to capacity peaking at 63.85 MW in 1399 before declining again. However, we acknowledge the need to more explicitly connect these patterns to specific policy mechanisms. We will expand table 3 to include quantitative indicators of policy effectiveness where available, such as investment rates, technology adoption timeframes, and capacity utilization factors. For policies where quantitative data is currently unavailable, we will clearly identify these as areas requiring further empirical investigation in our future research recommendations. This addition will provide policymakers with more concrete evidence of which interventions have demonstrated measurable impacts in Iran's specific context, strengthening the practical utility of our co-evolutionary framework.

8. Extracted problems and policy suggestions

The systemic problems identified in the research are summarized in table 3, which is based on the output from focus group meetings with participants as outlined in the research method section. The table highlights the most critical issues emphasized by the majority of participants. A new category of systemic problems is introduced in this research, focusing specifically on the dynamics of contextual factors within the technological innovation system (TIS).

To strengthen the empirical foundation of our recommendations, we examined published research on comparable international cases where similar policy interventions have proven effective. Regarding our infrastructure development recommendation, Sirin and Ege documented how Turkey's dedicated renewable energy investment mechanism helped overcome infrastructural barriers despite political uncertainties, resulting in significant wind capacity growth, providing valuable lessons for Iran's context [54]. For institutional coordination, Karatayev et al. demonstrated how Kazakhstan's renewable energy framework effectively aligned energy pricing policies with sustainability goals, increasing investment while navigating the challenges of a transitional economy with strong fossil fuel interests similar to Iran's [55]. On technology transfer initiatives, Fadly analyzed how targeted international partnerships enabled Egypt to advance its renewable energy sector while navigating complex geopolitical dynamics [56]. At the same time, Lilliestam et al. provided similar insights for various Middle Eastern countries [57]. Additionally, Luomi provided empirical evidence on how grid enhancement programs in the Gulf Cooperation Council countries effectively addressed geographical distribution challenges similar to those in Iran [58]. These studies collectively support the potential effectiveness of our recommendations when adapted to Iran's specific circumstances.

This research demonstrates that the growth of the wind energy innovation system in Iran was positively influenced when contextual factors had favorable effects, whereas negative contextual factors caused stagnation and hindered progress. The relationship between contextual and structural factors highlights the importance of considering their dynamics in future policies for sustainable wind energy development. Based on these findings, several policy suggestions are offered for promoting the wind energy innovation system in Iran:

- Stabilization and improvement of financial and technical infrastructure: A stable infrastructure, including long-term financing for wind projects and technical facilities to connect to the power grid, is essential to encourage private investors to participate in the sector.
- Supporting actors and institutions in renewable energy: Policymakers should provide financial incentives and legal support to key players, such as turbine manufacturers and private investors, to foster the development of the wind energy market.
- Formulation of stable policies and avoidance of frequent law changes: Political instability and frequent changes in laws have hindered the sector's growth. Establishing consistent policies and laws will help build investor confidence.
- Increasing inter-sector interactions and international cooperation: Enhancing domestic collaborations and strengthening international partnerships will facilitate knowledge and technology transfer, accelerating wind energy development.
- Strengthening the role of renewable energy policy institutions: Regulatory bodies should focus on creating and implementing renewable energy laws, fostering coordination between sectors to ensure sustainable wind energy development.

Table 3. Comprehensive inventory of systemic problems identified through focus group meetings and expert interviews, categorized by their type (functional, structural, or contextual) and point of impact.

Type		The problem	Point of impact
Functional factors	Entrepreneurship	Low entry rate of private companies and entrepreneurs in the wind industry	-
	Knowledge development	Lack of technical knowledge of construction and design, especially in essential parts with high added value of wind turbine	-
	Dissemination of knowledge	Very few international collaborations in scientific and industrial fields	-
	Orientation to the system	Weak implementation of laws and policies for the development and distribution of wind energy	-
	Providing resources	Low rate of private sector investment in the wind turbine industry	-
		Non-fulfillment of the resources foreseen in the laws and regulations of the government	-
	Legitimacy	Little familiarity of private investors with the benefits of wind energy	-
		Lack of belief in wind energy among political activists and officials, even managers of the Ministry of Energy	-
Dynamics of functional factors	Legitimacy, Financing	Reluctance of investors due to low awareness of wind power plants and renewable energies	Weakening of financial resources
	Orientation to the system, Entrepreneurship	The low motivation of investors to enter the wind energy industry due to the non-implementation of protective laws for wind power generation	Weakening entrepreneurship
	Legitimacy, Orientation to the system	Poor implementation of laws and regulations due to lack of knowledge or belief in wind power generation	Weakening system orientation
	Dissemination of knowledge, Knowledge development	Low capability in wind turbine design and construction due to weak international interactions	Weakening the development of knowledge
Structural factors	Institutions	Not allowing the export of electricity to wind power plants	Weakening of financial resources
	Interactions	Lack of strong trade union organization in the field of wind energy	Weakening system orientation
	Infrastructures	Lack of coordination of electricity transmission and distribution network with wind power plants	Weakening entrepreneurship
Contextual factors	Political factors	International sanctions	Weakening of financial resources
		Political nature of energy pricing and price suppression	The inability of the Ministry of Energy to repay investors
	Geographic factors	The long-distance of windy areas of the country from the main centers of electricity consumption	High costs of wind power transmission
	Other systems (oil and gas)	Low price and availability of gas	Reducing the cost of thermal power plants and making wind power production uncompetitive
		Predominance of gas abundance thinking	Providing gas at a meager price to power plants
	Electricity industry	Not allowing the export of electricity to wind farms	Weakening the function of entrepreneurship
		Conception of luxury goods and research to the development of wind power plants in the electricity industry complex	Weakening the function of directing the system
Dynamics of contextual factors	Political factors, Electricity industry	Failure to pay on time and, in total, the demands for the guaranteed purchase of wind power due to the budget deficit of the Ministry of Energy	Negative impact on entrepreneurship and financial resources
	Other systems, Electricity industry	Severe suppression of the price of electricity tariff due to the misconception of the abundance of natural gas and the inability of the Ministry of Energy to repay the guaranteed purchase of wind power	Negative impact on market shaping function
	Other systems, Electricity industry	The decrease in the cost of thermal electricity production due to the low price of gas supplied to these power plants and the subsequent uneconomical output of wind power.	Negative impact on market shaping and entrepreneurship

9. Conclusion

This paper explored the dynamics of Iran's wind energy innovation system, focusing on the background, structural, and functional factors that influence its life cycle. The findings suggest that Iran's wind energy innovation system is transitioning from the formation stage to the growth stage, but remains significantly dependent on contextual factors. This dependence hinders the system's full development and exposes it to vulnerabilities from changes in environmental factors. The analysis of the system's evolution over three periods showed that the co-evolution between contextual factors and the innovation system played a crucial role in determining its growth or decline. In the first period, favorable geographical conditions facilitated the initial formation of the wind innovation system, despite challenges from the fossil fuel system and political sanctions. These issues hindered the full development of infrastructure and the legitimization of wind energy; however, geographical factors provided positive momentum for the creation of institutions and functions related to wind energy.

In the second period, political factors, including sanctions and currency fluctuations, along with the lack of financial and technical infrastructure, negatively impacted the system. This led to reduced investor motivation and halted growth, resulting in a negative co-evolution between contextual factors and the wind energy system. As a result, the system's growth stage was not fully realized during this period. The third period saw a shift in policymakers' attitudes towards renewable energy, fostering a positive co-evolution between contextual factors and the innovation system. This change strengthened institutions, actors, and market development.

Based on our analysis, we recommend four critical policy interventions that would most effectively strengthen Iran's wind energy innovation system: (1) Establishing a dedicated infrastructure development fund with guaranteed long-term financing mechanisms resistant to political fluctuations; (2) Creating a coordinated institutional framework that aligns energy pricing policies with renewable energy goals while reducing bureaucratic barriers; (3) Implementing technology transfer initiatives through targeted international partnerships that can withstand geopolitical tensions; and (4) Developing comprehensive grid enhancement programs specifically designed to accommodate the geographical distribution of wind resources. These targeted interventions address the most persistent barriers identified in our co-evolutionary analysis and offer the highest potential impact for transitioning the system from formation to sustainable growth.

For future research, we recommend five concrete avenues of inquiry that would address critical gaps identified in this study:

(1) Longitudinal quantitative analysis tracking key performance indicators of Iran's wind energy innovation system over 10+ years to establish more precise correlations between policy interventions and system outcomes;

(2) Comparative case studies examining wind energy innovation systems in countries with similar contextual challenges (e.g., Turkey, Russia, Kazakhstan) to identify transferable strategies for overcoming political and infrastructural barriers;

(3) Sectoral integration research investigating optimal mechanisms for integrating wind energy with Iran's existing electricity grid, including technical specifications, cost-benefit analyses, and implementation roadmaps;

(4) Institutional ethnography examining decision-making processes within key energy governance bodies to understand how cognitive frameworks and organizational cultures influence wind energy policy implementation;

(5) Agent-based modeling of investor behavior under different policy scenarios to predict how specific incentive structures might accelerate private sector participation despite contextual uncertainties.

These research directions would provide crucial insights for both theoretical advancement of the co-evolutionary TIS framework and practical policy development in contexts where renewable energy transitions face complex institutional and geopolitical constraints.

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