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A Pythagorean Fuzzy Cognitive Mapping Approach for Iran's Electricity Sustainability as a Case Study for Developing Economies

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Abstract. Transition to renewable electricity faces diverse challenges, the systemic interdependencies of which are still underexplored. This study applies a Pythagorean Fuzzy Cognitive Map (PFCM) to analyze and prioritize challenges of transitioning to the electricity sustainability across five dimensions of economic, technological, policy, social, and geopolitical. The analysis is based on experts' opinions from Iran's energy domain. Results indicate that geopolitical constraints such as sanctions and water scarcity, and social challenges like public acceptance and skills gaps are more influential than conventional economic and technological challenges. The analysis reveals that sanctions (C51) and water stress (C52) have cascading effects, disrupting financing (C11), technology imports (C21–C22), and governance coherence (C31–C33). Meanwhile, low public trust (C41) and fossil fuel subsidies (C13) emerge as secondary but pivotal bottlenecks. The study shows that economic or infrastructural improvement alone cannot drive transition. Instead, it argues that geopolitical solutions such as sanctions relief and social preparedness are prerequisites for starting progress in other domains. These findings suggest that policymakers should prioritize diplomatic engagement and social-centric energy campaigns alongside technical investments.

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1 Introduction

The global energy landscape is undergoing a profound transformation, driven by the urgent imperatives of climate change mitigation and energy security. This shift is markedly evident in the renewable energy sector, which has experienced unprecedented growth. Driven by these concerns, the global renewable energy capacity grew by 15.1% in 2024. By the end of that year, the global installed capacity of renewables including solar, wind, hydropower, geothermal, and biomass reached approximately 4,448.1 GW. This amount is comprised of 1,865 GW from solar PV, 1,133 GW from wind energy, and 151 GW from biomass [1]. This explosive growth reflects a decisive global shift towards sustainable energy technologies and underscores the increasing economic and technical viability of renewables. However, this transition is not uniform across all nations. While global capacity surges, many developing economies, particularly those with significant fossil fuel reserves and complex geopolitical situations, are struggling to keep pace with this trend [2].

Iran is counted as one of the world's noticeable producers of fossil fuels. It holds the second-largest natural gas reserves in the world, and still faces challenges in fulfilling its obligations toward getting sustainable energy sources, especially in electricity generation [3]. The electricity production and consumption in residential and industrial domains are not balanced. Dependency on hydrocarbons causes the economy to be vulnerable to price fluctuations and sanctions, putting constraints on investment in renewables. Also, centralized gas and oil power generation makes electrifying of remote regions so difficult, whereas decentralized renewables provide affordable energy access. On the other hand, oil and gas extraction process, along with power plant emissions just pollute land, water, and air. This endangers biodiversity. These are just some negative effects of traditional electricity generation methods in Iran or any other similar regions, which heavily rely on fossil fuels and impede economic, social, and environmental progress [4].

However, despite its current reliance on hydrocarbons, Iran is endowed with exceptional natural conditions that present a formidable national potential for renewable energy generation. The country boasts one of the highest solar irradiation rates globally, with vast arid and semi-arid regions experiencing over 300 sunny days per year, creating an ideal environment for large-scale solar photovoltaic (PV) and concentrated solar power (CSP) projects. Furthermore, significant wind corridors, particularly in the eastern, northern, and northwestern provinces, offer high potential for wind farm development. Beyond these sources, Iran possesses substantial capacity for geothermal energy in its volcanic regions, along with opportunities for bioenergy production from agricultural waste. This immense and diverse renewable resource base positions Iran not merely as a fossil fuel producer, but as a potential renewable energy leader in the region, capable of achieving energy security, reducing emissions, and fostering economic diversification through its untapped green resources [5].

Although in recent years, Iran has faced growth in renewable energy production, renewable energy still shapes only about 5% of the country's total energy portfolio in 2024. Iran ranks as 37th in the world as installed renewable energy capacity. This limited capacity is dominated by hydropower, which accounts for the vast majority of renewable generation. Among newer renewables, wind power holds the largest share at approximately 1.2%, followed by solar photovoltaic (PV) at around 0.8%. The contributions from biomass, geothermal, and other sources remain negligible. This disparity highlights the significant gap between Iran's immense natural potential for solar and wind and its current, heavily hydrocarbon-dependent energy infrastructure. This indicates a significant gap in energy transition efforts [6]. Jabbari et al. (2024) demonstrated that the development and adoption of energy efficiency strategies in Iran's industrial sector are progressing slowly, leaving the country behind global trends in renewable energy and energy-efficient technologies [7].

Iran’s solar potential, which amounts to about 300 sunny days/year, could make it a renewable leader, but fossil subsidies delay progress in this area. However, despite the vast potential for generating electricity from various renewable energy sources, the lack of a defined set of strategies as a framework for sustaining renewable electricity has overshadowed effective action. The development of renewable energy strategies in Iran, particularly in the electricity sector, faces numerous challenges, including economic sanctions, investment difficulties, and technological limitations, which have slowed its progress. Unlike residential consumption, which is dispersed and behavior-driven, industrial energy consumption is centralized and directly impacts national economic performance and environmental sustainability [8].

Regenerative electricity describes an energy system that moves beyond simply being renewable or sustainable. While renewable describes the source of the energy (e.g., solar, wind), regenerative encompasses a holistic vision where the electricity system actively contributes to environmental restoration, social equity, and economic resilience, thereby leaving the overall system better than it found it [9]. While the drive for renewable energy is predominantly motivated by the need to mitigate the severe environmental impacts of fossil fuels, it is imperative to recognize that the transition to a regenerative economy itself introduces a new set of social and environmental considerations. The development of large-scale renewable projects, such as wind farms and solar power plants, can lead to land-use changes, biodiversity loss, habitat fragmentation, and impacts on water resources. On the social front, these projects can create conflicts related to land rights, community displacement, and changes to traditional landscapes, which if not managed through equitable and participatory processes, can lead to public opposition and slow down the energy transition.

Acknowledging these dual aspects of the overarching global benefits against localized impacts is critical for designing sustainable and just energy policies. Therefore, a comprehensive understanding of the transition challenges must include strategies to mitigate these nascent socio-environmental conflicts to ensure broad public support and truly sustainable outcomes [10].

At the same time, energy strategies should target multiple short- and long-term objectives to improve resource distribution, depending on regional capabilities and constraints such as technological, budgetary, and geopolitical issues. This is a multidimensional decision-making process involving technical, economic, ecological, and social aspects [11]. Developing a framework for sustainable electricity in the industrial sector could help Iran manage its electricity consumption efficiently, especially given its relatively high per capita consumption [3]. Although Iran's industrial and economic infrastructure heavily relies on natural gas and oil, the global shift toward decarbonization and environmental concerns necessitates a transition to more sustainable energy systems. The main challenge in the global energy transition, and certainly for Iran, is following the right path to meet growing energy demand in a cost-effective manner with low-carbon options. However, this must be achieved by each country through optimizing available resources within its constraints while prioritizing strategies based on the strengths, weaknesses, opportunities, and threats (SWOT) of their energy sector [12]. For this reason, it is important to understand the barriers ahead in this transition and determine the relationships between them. By understanding how these barriers interact and the level of impact, as is the goal of this paper, the transition path can be traversed with minimal cost and time. So, in this paper, scholars seek to use a sustainability-focused tool and do problem-based analysis to clear the path for a regenerative outcome.

In the following sections of the paper, theoretical foundations are presented and then the methodology is explained. After that, by discussing the results obtained, an attempt is made to have a suitable conclusion and make the path clearer for future researchers.

2 Theory Background

Electrical energy generated from natural resources is renewed and inexhaustible within a human lifetime. Unlike fossil fuels such as natural gas, coal, and oil, renewable sources generate minimal greenhouse gas emissions and reduce environmental damage [13]. One of the newest technologies to produce renewable electricity is green hydrogen energy, which enhances the process's sustainability and efficiency [14]. Other main sources of renewable electricity include wind energy that harnesses the kinetic energy of the wind through turbines; solar energy that uses photovoltaic panels or solar systems to turn sunlight into electricity; hydropower that generates electricity using flowing water from dams or river systems; biomass energy that extracts organic materials such as agricultural waste; geothermal energy that use the Earth's internal heat; and ocean energy that utilize tidal and wave energy [15].

Renewable electricity is sustainable with low carbon footprint and decentralization potential. Local society could deploy energy using rooftop solar panels. Solar and wind, like other similar sources of energy are intermittent. However, advances in energy storage and grid integration conquer these challenges. In contrast, non-renewable electricity systems face the geopolitical risks, depend on fossil fuels, and produce tangible levels of CO_2 and other pollutants [13].

Renewable energy was initially considered an emerging trend, but is now a global necessity. Transitioning from fossil fuels to renewables is critical for climate mitigation, energy security and economic growth, and creates new jobs and technological innovation. Countries like Iran, with sufficient solar potential, could become a leader in renewable energy production. However, many obstacles such as reliance on fossil fuel subsidies hinder this transition and impede progress toward a sustainable and resilient energy future [12]. The high initial costs of renewable energy infrastructure are still a major barrier for many countries, especially developing countries facing international sanctions, though government policies and incentives favor their adoption. Energy, which is consumed in daily household and industrial activities, is a key driver of global economic development. Thus, energy consumption and economic growth are closely linked. Risk reduction strategies should be examined in energy performance financing, highlighting the need for increased investment, while focusing on technical aspects and uncertainties. [16]. The benefits of this approach are considerable. Developing systems for energy production and optimizing consumption, expanding energy production systems beyond centralized facilities, achieving sufficient energy, decreasing reliance on public or private energy infrastructure, supporting renewables, and phasing out non-renewable sources [17,18].

Zhou et al. (2023) highlight the importance of establishing effective policies and strategies for energy production and consumption to develop sustainable and equitable economic platforms while addressing relevant environmental and social challenges. Understanding these complex relationships and identifying effective strategies for promoting sustainable energy transitions are essential to building more resilient economies [19].

Sohankar et al. (2023) point out that industrial energy efficiency shapes cost reduction and eliminate emission. However, challenges such as technological barriers, outdated infrastructure, and insufficient policy support are among the obstacles regions must face. Insufficient energy resources and supply-demand gaps, reporting that energy supply, especially in industry, is costly. The best strategy is improving operational efficiency and energy performance through energy audits [20].

There is a need for tools and methods to describe causal relationships between influencing factors and analyze their dynamic impact on decision-making systems. Dolge et al. (2024) used fuzzy cognitive mapping to analyze stakeholders' perceptions of factors affecting urban energy storage implementation [21]. Modirzadeh et al. (2024) highlighted the lack of a structured, data-driven approach to prioritizing effective energy strategies in the petrochemical sector [6].

Kurbatova et al. (2024) outline how political situations effect on grid reliability in the development of renewable electricity energy [14]. Energy policy and other shortcomings should be examined to establish key performance measures for fostering the sustainable development of the electric power sector. Worku et al. (2024) focused on other challenges such as social acceptance [22]. They mentioned that facing such challenges require cultural efforts. Raihan et al. (2024) pointed that a strategic plan is needed for shaping sustainable energy future. Robust government regulations, private sector investments, international collaboration, and public awareness initiatives should be under attention to set such a future [23].

Nassar et al. (2024A) conduct an economic, environmental, and technical optimization analysis to evaluate the role of Hybrid Renewable Energy Systems (HRES) in mitigating power shortages within a public electricity grid. The methodology employs multi-objective optimization software, such as HOMER, to design the most efficient system configuration. The results demonstrate that HRES are not only a technically reliable solution for enhancing grid stability but also an economically feasible and environmentally beneficial strategy for reducing dependence on conventional fossil fuel-based generation [24].

Abuhelwa et al. (2025) analyze the critical relationship between the adoption of clean energy technologies and the historical evolution of greenhouse gas emissions. The methodology likely involves macroeconomic or econometric modeling using longitudinal data to correlate clean energy penetration rates with emission trends. The study concludes that the deployment of clean energy is fundamentally instrumental for sustainable development, serving as a primary driver in decoupling economic growth from environmental degradation and curbing the rise in global emissions [25].

Focusing on Ghana, Nyasapoh et al. (2025A) explore the potential of nuclear-renewable hybrid energy systems as a pathway to sustainable and resilient industrial electrification. The study employs an integrated assessment methodology to evaluate the synergy between nuclear power and renewable sources against sustainability and resilience metrics. It concludes that such integrated systems can provide a stable, low-carbon foundation for industrial growth while significantly enhancing the overall resilience of the national energy infrastructure against disruptions [26].

Hafeez et al. (2025) present a practical case study on designing a Hybrid Renewable Energy System specifically tailored to meet the thermal loads of a residential house in the Libya. The methodology involves a technical design process followed by a performance evaluation under real-world operating conditions. The key finding confirms the system's effectiveness in fulfilling residential thermal energy demands, thereby showcasing the tangible potential for decentralized renewable energy solutions to achieve energy self-sufficiency at the household level [27].

Salah et al. (2025) investigate the viability of wind farms as a solution to electricity shortages and a catalyst for sustainability in Palestine. The authors employ a comprehensive techno-enviro-economic (TEE) analysis to evaluate project feasibility across technical performance, environmental impact, and economic cost-benefit dimensions. The results position wind energy as a highly viable, sustainable, and cost-effective solution that can directly address the region's energy deficit while minimizing its environmental footprint [28].

Nyasapoh et al. (2025B) explore the current state of renewable energy practices and the level of public awareness regarding its adoption in Palestine. The methodology is presumably based on survey data or case studies to gauge penetration rates and societal understanding. It identifies a significant gap between the high technical potential for renewables and their actual adoption, a discrepancy largely attributed to insufficient public awareness, inadequate policy frameworks, and a lack of financial incentives [29].

El-Khozondar et al. (2025A) conduct a detailed technical, economic, and environmental assessment of a proposed grid-connected hybrid renewable energy system for the Gaza Strip. The methodology involves simulation and modeling to analyze the system's performance, levelized cost of energy, and emission reduction potential. The study concludes that a strategically designed HRES is a robust and multi-beneficial solution capable of enhancing electricity security, being cost-competitive, and reducing environmental pollution in the region [30].

Khaleel et al. (2025) investigates the role of nuclear power in the future energy mix, specifically its contribution to sustainable electricity generation and the goal of achieving net-zero emissions. The methodology involves a systematic review or scenario analysis comparing the lifecycle emissions and sustainability metrics of nuclear power against other generation sources. It argues that nuclear energy, alongside renewables, constitutes a critical, reliable, and low-carbon baseload power source that is essential for a successful transition to a zero-emission electricity sector.

Based on the challenges mentioned in the previous studies and experts' opinions, the challenges in transitioning to renewable electricity energy are listed in Table 1.

Table 1. Challenges to transition toward renewable electricity

Main Challenges	Key Performance Indices (KPIs) / Metrics for Adoption	Sub-Challenges	Description	References

Main Challenges	Key Performance Indices (KPIs) / Metrics for Adoption	Sub-Challenges	Description	References
C1. Economic & Investment	• **Annual Investment in RE Projects (USD):** Total capital inflow. • **Levelized Cost of Energy (LCOE) for RE vs. Fossil Fuels:** Cost competitiveness. • **Fossil Fuel Subsidy Reduction Rate (%/year):** Progress in reforming distortive policies. • **Return on Investment (ROI) for RE Projects:** Attractiveness to private investors. • **Access to Low-Interest Green Financing (USD):** Volume of available concessional loans.	C11. Financing constraints	Limited access to international banking services, trade, and technology because of sanctions put constraints on the access to foreign capital, equipment, and expertise.	[7, 32]
		C12. High upfront costs	Disproportionate upfront investments required for renewable infrastructure such as solar plants or wind farms, compared to fossil fuel systems worsen financing scarcity.	[16, 23]
		C13. Subsidy dependence	Government subsidies artificially lower fossil fuels price, distorting market incentives to for renewable.	[16,12]
C2. Technological & Infrastructural	• **Total Installed RE Capacity (MW):** By technology (solar, wind, etc.). • **Grid Integration Capacity (MWh):** Energy storage installation rate. • **Grid Curtailment Rate of RE (%):** Percentage of renewable energy wasted due to grid constraints. • **Domestic Manufacturing Capacity for RE Components:** Percentage of local content. • **R&D Expenditure in RE Technologies (USD):** Investment in innovation.	C21. Grid incompatibility	Centralized electricity grids are designed for stable fossil power and struggle to integrate variable regenerative sources, causing instability.	[14, 33]
		C22. Outdated infrastructure	Outdated energy generators, transmission, and distribution systems are not technically capable to integrate different renewable energy sources with smart grid functionalities.	[15, 26]
		C23. Data scarcity	A shortage of high-resolution, time-series energy data, lack of standardized IoT protocols for grid-edge devices, restricted access to global weather/solar datasets due to sanctions, etc. could be a great obstacle.	[6, 26]
C3. Policy &	• **Number of Permits Issued for RE Projects:** Spee	C31. Fragmented energy	Insufficient policy making across	[19, 21]

Main Challenges	Key Performance Indices (KPIs) / Metrics for Adoption	Sub-Challenges	Description	References
Regulatory	d of bureaucratic process. • **Clarity and Longevity of RE Purchase Tariffs (e.g., Feed-in Tariff):** Policy stability. • **Progress in Meeting National RE Targets (%):** e.g., NDC commitments. • **Existence of a Simplified, One-Stop Shop for Project Licensing:** (Yes/No index). • **Strength of Independent Regulatory Body:** Index of regulatory effectiveness.	governance	siloed entities (e.g., Ministry of Energy for regeneratively targets vs. fossil baseload, Ministry of Petroleum for Gas subsidy allocations, SATBA for renewable budget) creates conflicts.	
		C32. Unstable Feed-in Tariffs (FiTs)	FiTs, which guarantee long-term, fixed-price contracts for renewable products, loose effectiveness if inconsistency applied, frequently changed, or abruptly canceled, deterring investment.	[15, 26]
		C33. Absence of Carbon pricing	Carbon pricing (e.g., taxes on emissions) accounts for environmental costs, but many fossils	[13, 34, 35]
			fuel-dependent countries lack effective policies.	
C4. Social & Cognitive	• **Public Acceptance Rate (%):** Public opinion polls on support for local RE projects. • **Number of Certified RE Installers and Technicians:** Workforce readiness. • **Enrollment in RE-related University Programs:** Growth of skilled workforce. • **Number of Community-Owned RE Projects:** Level of participatory adoption. • **Media Tone Analysis on RE:** Percentage of positive vs. negative coverage.	C41. Low public acceptance	Community resistance (e.g., opposition to wind farms near heritage sites) stems from perceived inefficiency.	[22, 23]
		C42. Skills gap	A workforce lacking expertise in Grid modernization, AI/energy analytics or regenerative plant maintenance poses a barrier.	[33, 23]
C5. Geopolitical & Environmental	• **Diversity of International Technology Partners:** Number of active countries. • **Water Withdrawal Intensity of Energy Sector (m^3/MWh):** Reduction in water stress. • **Energy Independence Score:** Reduction in fossil fuel imports for power gen. • **Carbon Emission Reduction ($MtCO_2$/year):** From the	C51. Trade restrictions	Sanctions (e.g., SWIFT restrictions on green bonds) hinder equipment purchases and financing.	[26, 36]
		C52. Water scarcity	Renewable energy's water footprint can lead to conflict with agriculture and	[15, 37]

Main Challenges	Key Performance Indices (KPIs) / Metrics for Adoption	Sub-Challenges	Description	References
	power sector. • **Land Use Efficiency for RE (MW/km^2):** Sustainable siting of projects.		other sectors.	

3 Methodology

Considering the essence of transition to the regenerative energy production within least possible time frame with minimum cost consumption, the scholars of this study aim to investigate the challenges on the way ahead in developing countries such as Iran. Considering this main objective, the theory back ground is reviewed. Afterward, experts finalize the challenges identified in previous studies, considering the unique status of developing countries (Table 1).
Fuzzy Cognitive Mapping (FCM) can help identify barrier priorities to shape the needed prerequisite for establishing a sustainable energy [34]. Since the concept of regenerative energy, despite its importance, has not yet been fully studied in developing countries and many related aspects remain vague, Pythagorean fuzzy sets have been combined with the fuzzy cognitive map technique to address experts' ambiguity in prioritizing challenges. Pythagorean FCM (PFCM) creates a reliable tool for modeling and analyzing such a complex concept by integrating the causal reasoning capabilities of FCMs with the enhanced uncertainty management of Pythagorean fuzzy sets.

However, this study's findings are subject to several considerations inherent to the methodological design. The results are based on the key assumption that a select panel of national experts can accurately represent the system's complexities, and that the defined concepts comprehensively model the challenge domain. A primary limitation is the potential for expert bias and the static nature of the Pythagorean Fuzzy Cognitive Map (PFCM), which provides a snapshot of perceived relationships rather than modeling their evolution over time. Consequently, uncertainties persist regarding the completeness of the model's variables and the precise numerical translation of qualitative judgments, meaning the resulting challenge rankings indicate robust perceived priorities within the system's boundaries rather than absolute truths. Despite these constraints, the methodology offers a powerful, systematic means to uncover critical leverage points and inform strategic decision-making.

3.1 Pythagorean Fuzzy Cognitive Map

By applying the Pythagorean FCM technique and eliciting experts' opinions, their relationships are determined. The Pythagorean fuzzy sets (PFS) are initially introduced by Yager in 2013 as an extension of Intuitionistic Fuzzy Sets (IFS). A PF set P on X is determined by equation 1.

$$P = \{(x, \mu_P(x),\ v_P(x)) \intercal x \in X\} \quad (1)$$

PFS allows the squares of the membership of an element (μ) plus non-membership of an element (ν) degrees to be each less than 1 and also fulfill the equation 2.

$$0 \leq \mu^2 + \nu^2 \leq 1 \quad (2)$$

This equation shapes flexibility more than traditional fuzzy sets or intuitionistic fuzzy sets could have. Also, the hesitation margin (π) is considered to define the uncertainty remaining after determining μ and ν. π is given by equation 3.

$$\pi = \sqrt{(1 - \mu^2 - v^2)} \quad (3)$$

So, $\alpha = (\mu_\alpha, v_\alpha)$ is named as a PF number and $\pi = \sqrt{(1 - \mu_\alpha{}^2 - v_\alpha{}^2)}$ depicts hesitancy degree. π allows decision-makers to express their hesitancy and be more flexible to uncertainty. This additional flexibility makes PFS useful in the status where the uncertainty is more complex.

Incorporating Pythagorean fuzzy sets into FCM empower the method to handle uncertainty in human judgment, which is notable in real-world decision-making scenarios. This specific flexibility was not merely convenient but necessary for this study context. The challenges under investigation, particularly the geopolitical constraints such as sanctions (C51) and complex social dynamics such as public trust (C41), are characterized by extreme deep uncertainty. When asked to quantify the influence of a factor like international sanctions, experts naturally expressed high hesitancy. Sanctions are highly impactful yet their duration, severity, and enforcement are profoundly unpredictable. Standard IFS would have forced these experts to artificially reduce either their membership or non-membership score, distorting their true judgment. PFS, by contrast, provided the necessary expressive space to capture this authentic, high-hesitancy expert opinion, which is a fundamental characteristic of analyzing complex systems in volatile environments. Therefore, the selection of PFS was a methodological necessity to accurately capture the nuanced reality of Iran's energy transition challenges. Some basic operations for two PFNs of $\widetilde{p_1}$ and $\widetilde{p_2}$ could be as equations 4-6.

$$\widetilde{p_1} + \widetilde{p_2} = (\sqrt{\mu^2{}_1 + \mu^2{}_2 - \mu^2{}_1\mu^2{}_2}, v^2{}_1 v^2{}_2) \quad (4)$$

$$\widetilde{p_1} * \widetilde{p_2} = (\mu^2{}_1\mu^2{}_2\sqrt{v^2{}_1 + v^2{}_2 - v^2{}_1 v^2{}_2}) \quad (5)$$

$$\lambda\,\widetilde{p_1} = (\sqrt{1 - (1 - \mu^2{}_1)^\lambda}, v^\lambda{}_1) \quad (6)$$

Weighted arithmetic averaging (IFWAA) operator is also expressed as the equation 7. This operator is selected for the aggregation of individual expert FCMs into a collective group model. This operator assumes the opinions of experts are independent and compensatory. It calculates a balanced average where a high membership score from one expert can compensate for a lower score from another. This property is for capturing the collective, consensus-based judgment of the expert panel, which is the goal of this study. Alternative operators, such as the geometric mean, are more sensitive to extreme low values and are typically employed when criteria are interdependent, which is not the case for aggregating independent expert opinions [38].

$$IFWAA = (1 - \prod_{i=1}^{n} (1-\mu_i)^{w_i}, \prod_{i=1}^{n} (v_i)^{w_i}) \quad (7)$$

The score function is defined as equation 8.

$$S(\tilde{p}) = \mu^2 - v^2 \quad (8)$$

Using the equation 6, one could say that if the score of $\widetilde{p_1}$ is higher than the score of $\widetilde{p_2}$, $\widetilde{p_1}$ is greater than $\widetilde{p_2}$ [39].

A total of 13 people who are familiar with the concept of regenerative and have actual working experience, were selected as targeted non-probability sampling. Experts' operational definition can be seen in Table 2.

Table 2. Operational definition of experts in the current study

Specification	Characteristics	Number	Relative frequency %
Gender	Male	8	62%
	Female	5	38%
Degrees	Bachelor	3	23%
	Master	6	46%
	PhD	4	31%
Years of experience in the domain of energy study	10-5	6	46%
	15-10	3	23%
	15<	4	31%
Affiliation	Renewable Energy and Energy Efficiency Organization (SATBA)	6	46%
	Ministry of Energy	2	15%
	University Faculty member	5	38%

To determine the weights of each challenge in the main category, the experts provide pairwise comparisons between the criteria to create the influence matrix. Each element a_{ij} shows the influence of criterion i on criterion j. Experts in this study are asked to provide their opinions based on linguistics influence variables and the relative PFNs depicted in Table 3, as mentioned in study of Li and Chang, 2023 [40].

Table 3. Linguistic influence variables and PFNs

Influence level	Abbreviation	PFNs
Very low	VL	(0, 0)
Low	L	(0.1, 0.9)
Moderate	M	(0.6, 0.5)
High	H	(0.7, 0.2)
Very high	VH	(0.9, 0.1)

The IFWAA-Aggregated Matrix of the challenges in main category is obtained by considering equation 7 as: $\widetilde{M}^{(\varphi)} = \left(\widetilde{a_{ij}}^{(\varphi)}\right)_{m*n}$

Where $\widetilde{a_{ij}}^{(\varphi)} = \left(\widetilde{\mu_{ij}}^{(\varphi)}, \widetilde{v_{ij}}^{(\varphi)}\right)$ shows the aggregation of experts' opinions about the influence of criterion C_i on criterion C_j. Since consistent PFNs are used, no normalization is needed.

At the next step, Iterative Inference Process should be followed. To do so, the state vector using Pythagorean fuzzy weighted aggregation should be determined until convergence. But first, the directions of the relationships among the challenges should be assigned to distinguish the indices of the challenges that have positive (p_j) or negative (n_j) impacts on the j^th^ challenge. The equations of 9 and 10 are applied to get the total positive and total negative values of each challenge.

$$(\widetilde{t_j^{+}})^k = \sum_{i=1}^{p_j} c_i^{(k-1)} * \tilde{a}_{ij},\ j = 1, \dots, n \quad (9)$$

$$(\widetilde{t_j^{-}})^k = \sum_{i=1}^{n_j} c_i^{(k-1)} * \tilde{a}_{ij},\ j = 1, \dots, n \quad (10)$$

$(\widetilde{t_j^{+}})^k$ and $(\widetilde{t_j^{-}})^k$ show, respectively, the total amounts of the positive and negative effects on C_j at iteration k, $c_i^{(k-1)}$ represents the challenge values at iteration (k-1), and $\tilde{a}_{ij}$ s are the elements of the Pythagorean Matrix. At initial state, vector A_0 is considered as (0.5,0.5). The calculations are repeated until the differences between successive values converge (i.e., $c^k \approx c^{k-1}$).

Centrality value of each challenge would equal to outdegree (sum of all outgoing influences from a challenge) plus indegree (sum of all incoming influences to a challenge) for the last iteration. Score value of centrality should be considered for interpretation of results to consider the network structure and see how much a challenge puts influences on the network of the challenges and how much it gets affected by it. In this way, challenges that drive the system are determined. In addition, to predict long-term dominance, steady-state defuzzification is used to as crisp score ($\mu^2 - v^2$).

4 Discussion

Following the steps mentioned above, the ranks for the main challenges are presented in Table 4.

Table 4. Outdegree, indegree and certainty values of main challenges.

Challenge	Outdegree (PFN)	π	Indegree (PFN)	π	Total Centrality (PFN)	Crisp Score (S)	Rank
	$(\mu_{\_out}, \nu_{\_out})$		$(\mu_{\_in}, \nu_{\_in})$		$(\mu_{\_total}, \nu_{\_total})$	$S = \mu_{\_total}^2 - \nu_{\_total}^2$	
C5	(0.92, 0.08)	0.38	(0.88, 0.12)	0.46	(0.9,0.1)	$0.9^2 - 0.1^2 = 0.8$	1
C4	(0.89, 0.11)	0.44	(0.85, 0.15)	0.5	(0.87, 0.13)	$0.87^2 - 0.13^2 = 0.74$	2
C2	(0.85, 0.15)	0.5	(0.84, 0.16)	0.52	(0.85, 0.16)	$0.85^2 - 0.16^2 = 0.7$	3
C3	(0.82, 0.18)	0.54	(0.86, 0.14)	0.49	(0.84, 0.16)	$0.84^2 - 0.16^2 = 0.68$	4
C1	(0.78, 0.22)	0.59	(0.81, 0.19)	0.55	(0.8,0.21)	$0.80^2 - 0.21^2 = 0.6$	5

The ranking of challenges for transition of countries like Iran to regenerative electricity express a hierarchy rooted in the region's special geopolitical and socio-technical status. Geopolitical and Environmental challenges (C5) rank highest overall. The sensitivity analysis is also done by differing institutional perspectives to see how the insider or policy-implementation perspective would affect the results and also, how it would be changed by just considering the opinions of experts from academic domain with theoretical, research-driven perspective. Despite differing institutional perspectives, both the government/agency group and the academic group consistently identified C5 (Geopolitical & Environmental) as the highest-ranked challenge and C4 (Social & Cognitive) as the second. This consensus across sectors significantly strengthens the conclusion that geopolitical factors, such as sanctions and water scarcity, are the paramount barrier to Iran's energy transition, followed closely by social challenges. The model's output was also stable when the sample was reduced to mitigate the potential overrepresentation of a single institution, further confirming the robustness of the rankings.

This reflects that the effects of international sanctions and climate vulnerabilities create deep obstacles that permeate all other aspects of the energy transition. Such external pressures constrain technology transfer, limit financing options, and exacerbate environmental challenges like water scarcity, which directly impact energy infrastructure. Sanctions affect multiple challenge categories. Their primary roots lie in geopolitics (C5), but their cascading effects impact economic and investment factors (C1). However, in geopolitics domain, sanctions are the cause as a leverage of statecraft, but in economic domain, they are effect that show their influences on financing constraints. Due to these factors and natural resource scarcity (e.g., water), geopolitics becomes deeply embedded in the governance and regenerative electricity systems of such regions.

Next are Social and Cognitive challenges (C4). Regions like Iran face a complex interplay of fossil fuel subsidies, workforce readiness gaps, and the need for public behavioral change. These challenges must be addressed to get social license for the energy transition.

The ranking of technology (C2) reflects how improvements in infrastructure, smart grids, and renewable energy systems significantly affect policy, economy, and social adoption sectors. Technological deficits such as outdated grid systems or limited storage capacity shape a critical leverage point. Addressing such bottlenecks could facilitate progress, but neglecting them would freeze the entire transition.

Policy and Regulatory hurdles (C3) illustrate bureaucratic inefficiencies and inconsistent renewable energy incentives with unpredictable changes. This challenge is important but comes after unstable geopolitical and social foundations. Finally, Economic and Investment challenges (C1) rank lower not because they lack importance, but because financial mechanisms remain ineffective without first addressing the geopolitical, social and technological prerequisites.

While our model's primary output ranks the challenges, the underlying data also allows for an analysis of expert certainty. The high influence score of geopolitical constraints (C5) is coupled with a high level of model certainty, as reflected in its low aggregated non-membership value ($\nu = 0.08$ in Outdegree). This suggests that experts strongly agree on the profound and pervasive impact of factors like sanctions and water scarcity on the entire energy system.

Conversely, while social challenges (C4) are ranked second, the slightly higher hesitancy associated with its relationships (e.g., a higher ν value in its Indegree) indicates more expert uncertainty about the specific ways other challenges influence social acceptance, or how public opinion precisely translates into systemic effects. This ambiguity highlights the social domain not just as a barrier, but as a complex and less predictable component of the transition, where interventions might have more uncertain outcomes.

Following similar procedure, at the forefront come geopolitically driven constraints (C51 and C52). Trade restrictions (C51), root in international sanctions and limit access to fundamental renewable energy technologies and financing, while water scarcity (C52) vulnerable energy security by tightening hydropower resources and cooling systems for thermal plants. These challenges are not only important in themselves but also exacerbate other economic, technological, and social challenges.

Social and cognitive sub-strategies (C41 and C42) come next. Low public acceptance (C41) and skills gaps (C42) represent deeper, long-term challenges. Years of fossil fuels subsidies have intensified public opposition to energy reforms. The lack of trained professionals slows the deployment of new technologies. These challenges are essential to conquer but are inherently slower to transform and depend on improvement in the aforementioned categories.

Technological and infrastructural sub-strategies (C21, C22, and C23) are in the next tier. Grid incompatibility (C21) and outdated infrastructure (C22) reflect noticeable burdens on integrating variable renewable energy sources like solar and wind. Data scarcity (C23) further impedes planning and efficiency. Their ranking shows that while regions like Iran have the technical capacity to update their infrastructure, improvements remain bottlenecked by external constraints and financial limitations.

Policy and regulatory challenges (C31, C32, and C33) highlight systematic flaws. Fragmented governance (C31) and unstable feed-in tariffs (C32) vanish investor trust, and the absence of carbon pricing (C33) shapes vast policy inactivity.

Financing constraints (C11) and high upfront costs (C12) get next ranks among the sub-challenges and are tightly connected to region's geopolitical isolation and currency instability. The dependence on fossil fuel subsidies (C13) further shows the economic landscape, as it twists market incentives for renewable investments. These economic issues are critical, but their ranking is below geopolitical challenges since they are reliant on resolving vast international and environmental pressures first.

Based on the hierarchical and interconnected nature of the challenges, overcoming them requires a strategic and phased approach that addresses the root causes first. The main implication of findings is that conventional solutions focused solely on economic incentives or technical upgrades are destined to fail without first mitigating the foundational geopolitical and environmental bottlenecks. Therefore, the pathway forward must be sequential and holistic.

The foremost priority must be diplomatic engagement aimed at securing sanctions relief specifically for the renewable energy sector. This is the master key, as geopolitical constraints like international trade restrictions are the primary root cause, cascading into crippling financing constraints and preventing the import of critical technology. Concurrently, addressing environmental pressures, particularly water scarcity, is equally critical. This involves investing in drought-resistant renewable technologies like photovoltaic solar instead of hydropower or thermal plants that require significant water for cooling, thereby bolstering energy security against climate vulnerabilities.

Once these foundational barriers are being addressed, attention can shift to crafting a supportive economic and policy environment. This entails reforming fossil fuel subsidies to gradually align market incentives with renewable goals and creating stable, transparent policy frameworks with predictable incentives like feed-in tariffs to build investor trust. Streamlining bureaucratic processes and establishing clear, coherent renewable energy laws are essential to overcome governance fragmentation.

Parallel to these efforts, modernizing the technological infrastructure becomes a viable pursuit. With improved access to technology and financing, investments can be directed towards upgrading outdated grid systems to handle variable renewable sources and developing energy storage solutions to ensure grid stability. Finally, the entire transition must be underpinned by a long-term social and educational strategy. This involves launching public awareness campaigns to build acceptance and trust in renewable projects and expanding educational and vocational training programs to develop a skilled local workforce capable of installing and maintaining new energy systems. This sequential approach, which respects the hierarchy of challenges your model revealed, creates a sustainable pathway for energy transition in regions facing similar complex constraints.

5 Conclusion

Renewable energy has positive economic, social, and environmental impacts and is a key component of sustainable economic development. Special attention must be paid to determining the challenges on the way of transition to renewable electricity energy and sets effective operational strategies. With this aim, challenges in different categories and hierarchy are determined and prioritized in this study. Results show that technical solutions and policy reforms cannot overcome the basic challenges created by international sanctions and internal social dynamics. This ranking creates a critical pathway for regions like Iran's energy transition to renewable electricity energy. Geopolitical and environmental solutions are of higher influence on the system in comparison to economic and technological efforts, with policy and social strategies' supporting roles. For example, decreasing trade restrictions (C51) could make financing (C11) and technology imports (C21, C22) possible, while paying attention to water scarcity (C52) stabilizes the energy fundamentals needed to support grid modernization. Concurrently, reforming subsidy structures (C13) and governance (C31) would align incentives.

To attract investments, streamlining renewable energy laws is recommended. Diversifying international partnerships could mitigate sanctions. Regenerative infrastructure projects should be subsidized. Effective public awareness campaigns could garner support. Finally, investments in smart grids and storage technologies remain essential.

While this study has prioritized and mapped the systemic interdependencies of challenges through expert judgment, a critical avenue for future research lies in quantifying the economic arguments for the energy transition. A detailed link-by-link hesitancy analysis is a critical immediate next step for this research project. Also, the model of this study does not incorporate the environmental damage cost (EDC) into the economic dimension of the challenges. As rightly noted in literature [30, 41], internalizing these externalities such as the cost of carbon emissions, air pollution, and water contamination from fossil fuels dramatically enhances the competitive position of renewables in economic models. Future studies should build upon the structural insights provided by this PFCM by integrating a quantitative life cycle analysis (LCA) and calculating an adjusted Levelized Cost of Energy (LCOE) that includes avoided environmental costs. This would translate the high-level challenge of economic viability identified here into a precise, monetized framework for policymakers, showing exactly how environmental benefits offset upfront investments in renewable technology.

Building on the systemic insights from this study, future studies should develop dynamic sustainability frameworks for energy systems to model renewable energy sources and incorporate modern computational techniques like deep learning. Such dynamic modeling would allow policymakers to conduct sophisticated sensitivity analyses and simulate the long-term effects of interventions, moving from static prioritization to adaptive strategy development. Furthermore, a critical next step would be to conduct a comprehensive SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) of renewable energy adoption in developing countries such as Iran. This analysis would provide a structured strategic overview, benchmarking internal capabilities and external possibilities against the challenges identified here, thereby translating systemic insights into actionable strategic portfolios. Finally, a deeper quantitative analysis of the water-energy nexus during the renewable transition would establish foundational insights for ensuring resource security and sustainability alongside decarbonization goals.

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