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A Systems Thinking Approach to Energy Sector Stakeholder Engagement: Combining TSI, CSH, and DANP in a Society 5.0 Framework

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ABSTRACT

This study addresses the escalating energy challenges in Razavi Khorasan Province, exacerbated by reliance on fossil fuels and inefficient energy management. By employing a hybrid methodological framework combining Total Systems Intervention (TSI), Critical Systems Heuristics (CSH), and the DANP (DEMATEL-ANP) method, the research identifies and prioritizes key strategies to optimize energy systems. TSI enabled the systematic identification of stakeholders and systemic weaknesses, while CSH provided a critical lens to evaluate stakeholder roles and long-term sustainability goals. The DANP analysis identified clean energy infrastructure development, fostering public-private collaboration, and strengthening scientific institutions as pivotal strategies. The findings emphasize the need to transition to renewable energy, to enhance technological investments, and to foster cultural shifts in energy consumption. The study also highlights the significance of participatory governance and transparent decision-making in effectively addressing complex energy issues. By integrating environmental, technological, and public participation strategies, the proposed E-FLEX 5.0 framework offers a dynamic, scalable model for sustainable energy management. The outcomes underscore the potential for reduced dependence on fossil fuels, improved energy security, and sustainable development. This research contributes to addressing regional and global energy challenges and aligns with the goals of Society 5.0.

Keywords

Energy management, Renewable energy, Participatory Decision-Making, Society 5.0, DEMATEL-ANP.

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1. Introduction

The Global Energy Crisis of 2021-2023 began in 2021, following the COVID-19 pandemic, as much of the world faced shortages and price hikes in oil, gas, and electricity markets (Gholian-Jouybari et al., 2024). This crisis was driven by various economic factors, including a rapid economic recovery after the pandemic that outpaced energy supply (Ebrahimi et al., 2025), and it escalated into a global energy crisis following Russia's invasion of Ukraine in 2022 (Hussain et al., 2023). Natural gas prices reached record highs, leading to increased electricity prices in some markets. Oil prices also soared to their highest levels since 2008 (Khan, 2017). Higher energy costs pushed households into poverty, forced some factories to reduce production or shut down, and slowed economic growth (Yu et al., 2021). Europe, uniquely vulnerable due to its historical dependence on Russian gas, faced gas rationing during the winter of 2022-2023, while many emerging economies experienced surging energy import bills and fuel shortages (Van de Graaf, 2023). Global demand trends and the growth of gas consumption highlight that the Middle East alone has seen significant growth over the past 15 years, consuming as much gas as all of Europe (Lambert et al., 2022) (Figure 1).

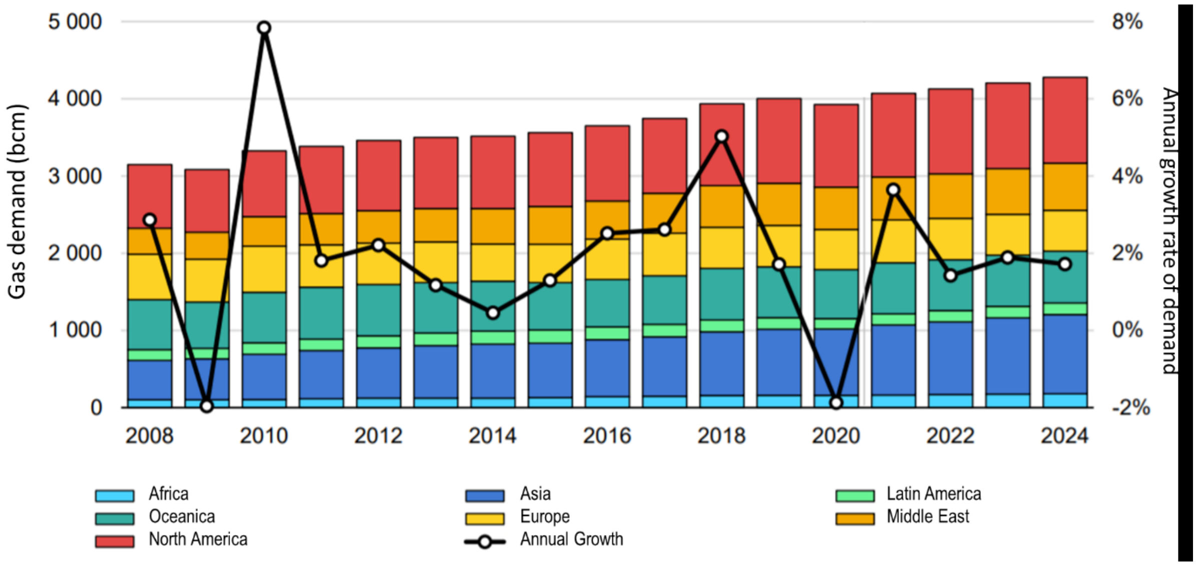

Figure 1. Global gas consumption and growth rate (Source: World Economic Forum)

In response to the global energy crisis, many countries adopted measures such as subsidizing coal and other polluting energy sources, reducing gas taxes, or lowering carbon-emissions costs (Bonakdari et al., 2025). While these short-term solutions reduced electricity bills, they contradicted efforts to limit global warming to 1.5°C, increasing the risk of a climate crisis (Gössling et al., 2023). European countries sought to boost gas imports from Algeria, Norway, and Azerbaijan, introduced gas storage commitments, and agreed on voluntary targets to cut gas and electricity demand by 15% through efficiency measures, renewable energy, and improved productivity Taghipour et al., 2023). The UK entered into a long-term LNG supply agreement with Qatar. In 2021, a U.S. producer signed three long-term supply contracts with China's Sinopec for LNG, doubling China's imports of U.S. natural gas. Gas prices in Europe dropped by 12% after Gazprom announced increased supply following the filling of Russian storage by early November. Norway ramped up gas production, and lower coal prices in China also helped reduce natural gas costs. However, regulatory issues and speculation drove emission quota prices to spiral, thereby increasing electricity costs (Liu et al., 2021).

In Iran, the energy outlook is equally challenging. Despite holding the second-largest natural gas reserves and being the fourth-largest producer (Mohaghar et al., 2025)Iran's gas sector faces numerous challenges (Slocum and Gessel, 2022). In 2022, gas production increased from 840–850 million cubic meters per day to 4 billion cubic meters per day, while annual consumption averaged 250 billion cubic meters, or 685 million cubic meters per day. Although sufficient on paper, seasonal spikes in winter demand lead to shortages (Keskar et al., 2023). In 2021, Iran exported 17 billion cubic meters of natural gas, with daily exports to Iraq rising to 35 million cubic meters to meet growing energy needs. Turkey, Iran's second-largest export market, imported about 9 million cubic meters per day in 2021 (Abdolahinia et al., 2024). However, Iran now faces its worst energy crisis in four decades, with potential social unrest as temperatures drop (Hussain et al., 2023).

According to the National Iranian Gas Company (NIGC), 60-70% of the country's gas production is consumed by the residential and commercial sectors (Heidari et al., 2022). This high consumption has caused fuel shortages in major industries such as cement, steel, petrochemicals, and power generation, resulting in an estimated $20 billion in lost revenue (Tickner et al., 2021). To address this, measures such as daily inspections of 4,000 government offices, a 50% penalty on gas bills for high-consuming offices, revised household gas tariffs penalizing overconsumption, and efficiency improvements in boiler systems have been implemented. A daily color-coded consumption map highlights excessive residential gas use in northern provinces and regions such as West Azerbaijan and Kurdistan, where consumption exceeds allowable per-household limits. Provinces such as Hormozgan, Khuzestan, Bushehr, and Sistan and Baluchestan adhere best to consumption guidelines. Moderate overconsumption is observed in provinces marked in orange, whereas red indicates severe excess; Mazandaran, Gilan, and Golestan exceed the standard limit by more than twice.

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To mitigate the crisis, the NIGC should implement targeted measures in high-consumption regions, such as prioritizing diesel for power plants or limiting gas supply to residential and industrial users in over-consumption provinces, to protect other provinces from the crisis. Decision-making appears centralized, sidelining participatory approaches (Nath et al., 2022). This study proposes a framework for participatory decision-making and policymaking in the energy sector, with a focus on the gas crisis.

The global energy crisis, coupled with the urgent need for sustainable solutions (Ehsanifar et al., 2023, Foukolaei et al., 2024, Ghaedi et al., 2024), highlights the importance of rethinking energy management frameworks (Ghaedi et al., 2024). Particularly in centralized energy systems, the lack of participatory decision-making and stakeholder engagement exacerbates inefficiencies and limits the potential for innovative, inclusive solutions. This research aims to address these gaps by proposing a comprehensive framework aligned with Society 5.0 principles, emphasizing technological integration, stakeholder collaboration, and sustainability. The framework leverages advanced methodologies, including Total Systems Intervention (TSI) (Torlak, 2001) and Decision-Making Trial and Evaluation Laboratory (DEMATEL)-based Analytical Network Process (DANP), to develop actionable strategies that balance technological innovation (Tang and Tsai, 2024), environmental preservation, and public participation.

The purpose of this study is to develop a participatory decision-making model that addresses systemic challenges in the energy sector while aligning with long-term sustainability goals. By integrating advanced tools such as GIS, AI, and data mining with stakeholder-centric approaches, this research seeks to enhance transparency, inclusiveness, and efficiency in energy governance. Specifically, it focuses on the context of Iran's gas energy sector, providing actionable insights and strategies to optimize resource utilization and promote the adoption of renewable energy (Khazaei et al., 2025a). The integrative framework enables both the identification of systemic weaknesses and the prioritization of participatory strategies through quantitative and qualitative analyses. It contributes to the literature by bridging systems thinking and participatory energy governance and by offering a replicable methodological framework for regions facing similar centralized energy challenges.

The remainder of the paper is structured as follows: the literature review explores existing research on participatory decision-making and energy management, identifying gaps and opportunities. The methodology section details the application of TSI and DANP in developing the proposed framework. The results and discussion sections outline the key findings, highlighting the interconnectedness of strategies and their implications for sustainable energy management. Finally, the conclusion presents the study's contributions, practical implications, and directions for future research.

2. Literature review

2.1. Energy participation decision-making

Research on energy participation decision-making has explored diverse frameworks to enhance stakeholder engagement and social acceptance in renewable energy projects. Estévez et al. (2021) analyzed the integration of social criteria into renewable energy decision-making, reviewing 184 articles and identifying 490 social impact indicators using Multi-Criteria Decision Analysis (MCDA). Their findings highlighted critical social factors, including employment, governance, and social acceptance, while identifying challenges in expert consultation and stakeholder engagement, particularly in Asia and Europe. Wahlund and Palm (2022) investigated the concepts of energy democracy and energy citizenship within participatory energy transitions. Through a thematic literature review, they emphasized the differences between institutional governance in energy democracy and behavioral change in energy citizenship. Despite a focus on decentralized systems in Europe and North America, the study identified a lack of research on centralized systems.

Galende-Sánchez and Sorman (2021) critically reviewed participatory climate and energy initiatives to assess the potential for co-production. Their systematic review of 183 records revealed that genuine co-production remains rare, with consultation predominating. They called for innovative methods and stronger science-policy synergies to achieve transformational outcomes in developed countries. Zhou and Lund (2023) explored peer-to-peer (P2P) energy sharing and decision-making in smart communities. Their review highlighted the role of blockchain technology in enhancing transparency, security, and automation, as well as the economic and environmental benefits of P2P energy trading.

Stober et al. (2021) conducted a comparative analysis of 25 participatory renewable energy projects across Europe, focusing on inclusiveness and participation levels. Their findings revealed advanced practices in Western Europe and highlighted the importance of broad inclusiveness and substantive rationales for increasing social acceptance of renewable energy projects. Spyridonidou et al. (2021) developed a participatory framework for siting large-scale wind and PV farms in Israel using GIS and AHP tools combined with public and expert consultations. The framework successfully identified socially and environmentally suitable

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sites, showcasing the value of collaborative spatial planning. Stadelmann-Steffen and Dermont (2021) examined the role of political and economic participation in local renewable energy project acceptance. Their conjoint analysis revealed that while participation improves acceptance, its effectiveness varies by population group and mode of participation. Hanke et al. (2021) analyzed renewable energy communities (RECs) in Europe, finding that while RECs address energy justice, they often underrepresent vulnerable groups, emphasizing the need for broader inclusion.

2.2. Gas energy in iran

Iran's energy sector faces challenges in transitioning to a sustainable model while leveraging its vast natural gas resources. Tayebi et al. (2022) developed a decision support system (DSS) combining ANP, DEMATEL, and MULTIMOORA methods to prioritize air pollution control technologies in oil, gas, and petrochemical facilities. Their findings underscored the efficacy of technologies like electrostatic precipitators in supporting low-carbon policies. Pamučar et al. (2021) evaluated renewable energy potential in Iran's Caspian Sea coastline agriculture using MCDA techniques. Their analysis identified Mazandaran as the region with the highest bioenergy potential, informing sustainable energy strategies in agriculture.

Zahedi et al. (2022) explored strategic renewable energy policies in Iran, emphasizing wind energy for its economic and market advantages. They highlighted the potential for Iran to become a regional hub for renewable energy. Jamali et al. (2021) compared energy flow and greenhouse gas (GHG) emissions across irrigation systems in southern Iran. Their study demonstrated the superiority of sprinkler systems in reducing GHG emissions and improving energy efficiency compared to traditional methods. Taghvaee et al. (2022) analyzed energy efficiency improvements versus price policies in reducing fossil fuel consumption. Their dynamic modeling indicated that technology-driven efficiency improvements outperform price policies, yielding significant environmental and economic benefits. Noorollahi et al. (2021) modeled Iran's energy transition using the EnergyPLAN model. They found that efficiency improvements in thermal power plants and the expansion of renewable capacity significantly reduce CO_2 emissions and enhance energy system sustainability. Solaymani (2021) assessed renewable energy trends and policies in Iran, identifying challenges in scaling renewable energy. His study highlighted the need for diversifying policies and biomass utilization to reduce dependence on fossil fuels and promote sustainability.

2.3. Research gaps and novelties

Despite extensive studies on participatory energy decision-making, several gaps remain in both theoretical development and practical implementation. First, existing research primarily focuses on decentralized energy systems in developed contexts, leaving a significant void in understanding how participatory frameworks can be applied within centralized systems such as those in the Middle East. Second, most participatory initiatives emphasize consultation rather than co-production, resulting in limited stakeholder empowerment and insufficient integration of community perspectives into policy outcomes. Third, vulnerable and marginalized groups often remain underrepresented in participatory processes, raising concerns regarding energy justice, inclusivity, and equitable access to decision-making. Fourth, while several studies have applied tools such as GIS, AHP, and MCDA to support participatory planning, the use of emerging technologies, such as artificial intelligence, blockchain, and data mining, for participatory governance remains largely unexplored. Finally, in the specific context of Iran's energy sector, few studies address the intersection of stakeholder engagement, sustainability, and system-level transformation, despite the country's growing dependence on natural gas and pressing sustainability challenges. Addressing these gaps is essential to developing innovative, technology-driven, and participatory frameworks that enhance transparency, efficiency, and long-term energy resilience.

Most previous studies have relied on three main types of indicators to evaluate participatory energy systems: social, technological, and environmental. Social indicators focus on participation levels, inclusiveness, and public acceptance. Technological indicators address the integration of renewable energy, transparency, and system efficiency. Environmental indicators emphasize emission reduction and resource conservation. However, these metrics are often treated separately rather than within a unified framework, and their interdependencies remain unclear. This study addresses this gap by integrating these indicator categories into a coherent analytical framework within the E-FLEX 5.0 model, linking stakeholder participation to technological and environmental performance outcomes.

3. Methodology

The research methodology comprises three main stages. First, TSI is utilized to identify stakeholders, diagnose systemic weaknesses, and propose actionable solutions (Midgley and Rajagopalan, 2020) aligned with Society 5.0 (Deguchi et al., 2020). TSI adopts a flexible, meta-methodological framework that integrates multiple systems methodologies to analyze complex problems from diverse perspectives (Torlak, 2001). By systematically evaluating and revisiting methodologies, TSI ensures iterative refinement and adaptability to dynamic challenges, promoting a comprehensive understanding of systemic issues and opportunities (Nakamura and Kijima, 2011). Second, the DANP approach integrates DEMATEL and ANP techniques . This hybrid methodology leverages DEMATEL to establish causal relationships and ANP to prioritize criteria, eliminating the traditional need for pairwise comparisons. DANP's advanced approach addresses interdependencies among criteria, providing a robust framework for evaluating and selecting technology-driven solutions tailored to Society 5.0 requirements (Adel and Alani, 2024). Finally, a comprehensive development package for the gas supply system and fossil fuel management is formulated. This package consolidates findings from the TSI and DANP stages, offering a practical, participatory, and scalable roadmap. It emphasizes stakeholder engagement, technological innovation, and sustainability to address systemic inefficiencies and align with the goals of Society 5.0 (Ghobakhloo et al., 2024). The linguistic variables used in the fuzzy DEMATEL process were transformed into triangular fuzzy numbers as shown in Table 1, adapted from [49].

Table 1. Triangular fuzzy numbers for linguistic variables (Sorourkhah and Edalatpanah,2022)

Linguistic variable	Numerical scale	Triangular fuzzy numbers
No influence	0	(0, 0, 0.25)
Very low influence	1	(0, 0.25, 0.5)
Low influence	2	(0.25, 0.5, 0.75)
High influence	3	(0.5, 0.75, 1)
Very high influence	4	(0.75, 1, 1)

In this step, expert opinions are collected and averaged. Considering the input from P experts, P matrices (Z_1, Z_2, ..., Z_p) are obtained, where each element is represented by corresponding fuzzy numbers (Peng and Wang, 2018). To calculate the average matrix, the formula 1 is used.

$$Z_{ij} = \frac{Z^1 \oplus Z^2 \oplus \ldots Z^P}{P} \mathrm{z} \quad (1)$$

The resulting matrix is referred to as the "Initial Fuzzy Direct Relationship Matrix," where each element Zij of the matrix is expressed as a triangular fuzzy number (I_{ij}, m_{ij}, u_{ij}), representing the lower, middle, and upper values.

Step 3: Using equation 1, the standardization equation, the indicators' scales are transformed into comparable units. In the following equation, the matrix X is called the standardized direct relations fuzzy matrix (Wu et al., 2019):

$$a_{ij} = \left(\sum_{j=1}^{i} I_{ij}, \sum_{j=1}^{i} m_{ij}, \sum_{j=1}^{i} u_{ij}\right) \quad (2)$$

$$r = max_{1 \leqslant i \leqslant n}\left(\sum_{j=1}^{i} u_{ij}\right) \quad (3)$$

$$x_{ij} = \frac{Z_{ij}}{r} = \left(I'_{ij}, m'_{ij}, u'_{ij}\right) \quad (4)$$

Step 4: In this step, the fuzzy total relations matrix T is obtained. Each element x_{ij} of the matrix is represented as $(I'_{ij}, m'_{ij}, u'_{ij})$, where I', m', and u' correspond to the lower, middle, and upper values, respectively (Ardakani et al., 2024). These values are derived from the elements of the matrices X_u, X_m, X_I, which represent the lower, middle, and upper values in matrix X.

$$XI = \left[I''_{ij}\right], Xm = \left[m''_{ij}\right], Xu = \left[u''_{ij}\right] \quad (5)$$

Given that $t_{ij} = \left(I''_{ij}, m''_{ij}, u''_{ij}\right)$, we have:

$$\left[I''_{ij}\right] = X_I \times (I - X_I)^{-1} \quad (6)$$

$$\left[m''_{ij}\right] = X_m \times (I - X_m)^{-1} \quad (7)$$

$$\left[u''_{ij}\right] = X_u \times (I - X_u)^{-1} \quad (8)$$

This formula represents the identity matrix, while Xl, Xm, and Xu are n×n matrices, where the elements represent the lower, middle, and upper values of the triangular fuzzy numbers in matrix X, respectively (Ardakani et al., 2024).

Step 5: The row and column sums of matrix T are calculated using the specified formulas. These sums are critical for further steps in the analysis and help determine the relationships and influences among the criteria (Hasheminezhad et al., 2021).

$$\widetilde{\mathrm{D}} = \left(\widetilde{\mathrm{D}}_{\mathrm{i}}\right)_{n\times 1} = \left[\sum_{j=1}^{n} \widetilde{\mathrm{T}}_{\mathrm{ij}}\right]_{n\times 1} \qquad \widetilde{\mathrm{R}} = \left(\widetilde{\mathrm{R}}_{\mathrm{i}}\right)_{1\times n} = \left[\sum_{i=1}^{n} \widetilde{\mathrm{T}}_{\mathrm{ij}}\right]_{1\times n} \quad (9)$$

The matrices $\tilde{D}$ and $\tilde{R}$ represent n×1 and 1×n matrices, respectively.

Step 6: Determining the Importance of Indicators $(\widetilde{D}_i + \tilde{R}_i)$ and Relationships Between Criteria $(\widetilde{D}_i - \tilde{R}_i)$, If $\widetilde{D}_i - \tilde{R}_i > 0$, the corresponding criterion is influential (impacting other criteria, If $\widetilde{D}_i - \tilde{R}_i < 0$, the corresponding criterion is influenced (impacted by other criteria)

Step 7: Defuzzifying the Fuzzy Numbers $\widetilde{D}_i + \tilde{R}_i$ and $\widetilde{D}_i - \tilde{R}_i$

The fuzzy numbers obtained in the previous step are defuzzified using the following formula. In this formula, B represents the defuzzified value of a fuzzy number $\widetilde{A} = (a_1, a_2, a_3)$.

$$B = \frac{l + m + n}{3} \tag{10}$$

The ANP is a generalization of the AHP, in which relationships are not strictly hierarchical but are represented as a network that encompasses more complex interconnections. In this method, the first step is to model the problem's network structure (Emrouznejad and Marra, 2017). For this purpose, the DEMATEL method and its resulting structure are employed. Once the network is established, it identifies which main criteria influence one another (external relationships) and which sub-criteria within a criterion influence one another (internal relationships) (Nasrollahi et al., 2023). In the next step, pairwise comparisons must be conducted for each relationship in the network. According to Saaty's research, this involves fixing one factor while comparing it with the others (Saaty, 2004), a process that is notably complex and time-consuming. To address this issue, Chen and Lin (2018) proposed the fuzzy DANP method. In this approach, the full influence matrix generated by the DEMATEL method serves as the supermatrix for pairwise comparisons, thereby eliminating the need for the traditional, labor-intensive pairwise comparison process.

Step 8: Using the DEMATEL method, a network structure is established among the criteria, and the complete influence matrix is calculated for both criteria and sub-criteria (Kadoić et al., 2019). This matrix reflects the relationships and mutual impacts within the system.

Step 9: This step is performed twice: once for the complete influence matrix among the criteria and once for the complete influence matrix among the sub-criteria. Let the complete influence matrix derived from the DEMATEL method be denoted as T. To obtain the unweighted supermatrix (T_c^{α}), the data within each block corresponding to the sub-criteria of a criterion are normalized. The final matrix is constructed by arranging the normalized blocks together, and its transpose is considered the unweighted supermatrix (Ju et al., 2015).

$$T = \begin{bmatrix} T^{11} & \cdots & T^{1j} & \cdots & T^{1m} \\ \vdots & & \vdots & & \vdots \\ T^{j1} & \cdots & T^{ij} & \cdots & T^{im} \\ \vdots & & \vdots & & \vdots \\ T^{m1} & \cdots & T^{mj} & \cdots & T^{mm} \end{bmatrix}, \qquad T^{11} = \begin{bmatrix} T_{11}^{11} & \cdots & T_{12}^{11} & \cdots & T_{1m_2}^{11} \\ \vdots & & \vdots & & \vdots \\ T_{21}^{11} & \cdots & T_{22}^{11} & \cdots & T_{2m_2}^{11} \\ \vdots & & \vdots & \ddots & \vdots \\ T_{m_1 1}^{11} & \cdots & T_{m_1 2}^{11} & \cdots & T_{m_1 m_2}^{11} \end{bmatrix},$$

By dividing the elements of each row in the matrix T^{ij} by the sum of the elements in the same row and arranging them together, the normalized matrix T^{α} is obtained. The unweighted supermatrix is then defined as the transpose of the matrix derived in this step (Hsu et al., 2013).

$$T_c^{\alpha} = (T^{\alpha})'$$

Step 10: The unweighted supermatrix is used. Each block of the supermatrix corresponding to the main criteria is multiplied by the elements of the block related to the sub-criteria. This process yields the weighted supermatrix (W).

Step 11: After forming the weighted supermatrix, the final weights are determined by calculating the limit of the supermatrix. This step ensures the convergence of the matrix, providing the final priorities for the criteria and sub-criteria (Gölcük and Baykasoğlu, 2016).

$$\lim_{k \to \infty} W^k$$

3.1. Analytical process

To enhance the clarity of the analytical process, the study employed a structured, sequential approach that linked qualitative insight generation with quantitative validation. Using TSI, stakeholders and systemic weaknesses were first identified, and critical problem boundaries were refined through CSH. Expert panels then evaluated the interrelationships among the identified strategies using fuzzy linguistic variables, which were transformed into triangular fuzzy numbers and processed by the fuzzy DEMATEL method to quantify causal relationships and determine influence weights. The resulting influence matrix was normalized and integrated into the DANP framework, generating both unweighted and weighted supermatrices. Iterative computations continued until convergence, producing the final priority rankings for environmental, technological, and participatory strategies. This sequence of analytical steps enabled a transparent and replicable process for deriving data-driven conclusions from expert knowledge.

Each methodological component in this hybrid framework played a complementary role in ensuring methodological depth and coherence. TSI structured the intervention and guided stakeholder identification, while CSH offered a critical and reflective dimension that revealed discrepancies between current and desired system states. DANP then transformed these insights into quantifiable interdependencies, linking the systemic and participatory analyses to prioritized decision outputs. Together, these methods provided a coherent transition from problem diagnosis to strategic evaluation. The integrated process culminated in the development of the E-FLEX 5.0 model, which translates qualitative stakeholder perspectives into quantifiable, evidence-based policy recommendations for sustainable and participatory energy governance.

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3.2. Reliability and validity

To ensure the reliability and validity of the integrated approach, several validation steps were undertaken throughout the research process. First, methodological triangulation was applied by combining TSI, CSH, and DANP to cross-verify findings from qualitative and quantitative perspectives. The convergence of stakeholder insights (from TSI and CSH) with numerical prioritization (from DANP) provided internal validation for the proposed framework. Second, expert validation was conducted through iterative feedback sessions with 14 specialists representing academia, industry, and government. These experts reviewed intermediate outputs such as stakeholder maps, causal diagrams, and priority rankings to ensure conceptual coherence and practical relevance. Third, comparative validation was achieved by referencing the analytical sequence and outcomes against similar case studies in regional and international energy system research, ensuring consistency in methodological logic and interpretation of results.

Furthermore, sensitivity analysis within the DANP model was conducted by adjusting the fuzzy scales and re-evaluating the weight distributions to assess the robustness of the results under varying expert assumptions. The minimal variation in ranking outcomes confirmed the model’s stability. Finally, the feasibility of the proposed strategies in the E-FLEX 5.0 package was examined through discussions with regional policymakers, thereby providing contextual validation and assessing the practicality of implementation. These multi-level validation measures ensured that the study’s findings are both scientifically sound and contextually grounded.

4. Results

4.1. Case of khorasan razavi

The province of Khorasan Razavi, particularly its capital, Mashhad, is experiencing a severe energy and gas crisis. This stems from a combination of factors, including rapid population growth, harsh climatic conditions, and the province’s strategic role as a hub for industrial and residential energy consumption. Residential gas consumption in the province has steadily increased over the years, with peak demand during the colder months of December, January, and February. In 2022 alone, residential and commercial sectors accounted for 60-70% of the province’s gas production, creating a severe imbalance between supply and demand during the winter months. Consequently, energy-intensive industries such as cement, steel, and petrochemicals have experienced significant shortages, resulting in an estimated $20 billion in annual revenue losses.

Mashhad, as a densely populated urban center and a hub for religious tourism, exacerbates this crisis. Its high energy demand is attributable to population growth, tourism-related activities, and infrastructure expansion. The industrial sector, primarily located in regions such as Sarakhs and Neyshabur, relies heavily on natural gas for production processes. However, inefficiencies in distribution networks and outdated infrastructure have resulted in excessive energy waste. For example, regions such as Sarakhs, known for their rich gas reserves, are unable to meet the growing local demand due to outdated extraction and distribution technologies. Additionally, the lack of renewable energy integration has further strained the province's gas reserves, which remain the primary energy source (Taghipour et al., 2024).

Efforts to address the crisis have included measures such as revised household tariffs, inspections of government facilities, and penalties for overconsumption. Despite these interventions, the 2022 winter gas shortages in Razavi Khorasan underscore the inefficiencies in centralized decision-making and the absence of participatory approaches. Seasonal spikes in demand and reliance on fossil fuels, coupled with insufficient investment in renewable energy, have left the province vulnerable to energy crises. A shift toward sustainable solutions such as solar and wind energy, particularly in areas such as Binalood and Khaf, could alleviate the crisis. However, implementation remains slow, hampered by bureaucratic and financial barriers, leaving the province in a precarious energy state.

4.2. Land administration and expert alignment

In the early stages of our research, we used the comprehensive land-planning data for Khorasan Razavi to align perspectives among a diverse group of experts. The goal was to establish a unified understanding of the region's challenges and opportunities, particularly with respect to energy consumption and infrastructure development. The experts, with diverse backgrounds in economics, industry, and environmental science, initially presented varied and sometimes conflicting viewpoints. By facilitating structured discussions, we harmonized these perspectives, ensuring that everyone worked toward common goals. This alignment was critical for advancing the stages of the TSI methodology effectively. Through the TSI process, it became evident that Critical Systems Heuristics (CSH) would be the most appropriate approach for addressing the province's complex energy issues (Dehghan Nayeri et al., 2020). We applied CSH to refine our analysis by posing critical questions that guided experts in systematically

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evaluating the challenges and potential solutions (Khazaei et al., 2025b). These discussions not only clarified the objectives but also encouraged experts to adopt a holistic and collaborative perspective. The structured use of CSH helped us integrate diverse insights and foster a deeper understanding of the systemic issues at hand (Ramezani et al., 2021).

The panel of experts included individuals with experience ranging from 6 to 30 years in their respective fields, ensuring a blend of innovative and seasoned perspectives. Among the 14 participants, 50% held doctoral degrees in disciplines such as industrial management, environmental sciences, and chemical industries, while the others had advanced expertise in mechanical engineering, human resources, and project management. This group's diversity in age (29–55 years), gender balance (seven women and seven men), and professional backgrounds provided a rich pool of knowledge. Their collective expertise significantly contributed to the iterative refinement of our approach, enabling us to address the critical energy challenges in Khorasan Razavi with a comprehensive and forward-looking strategy.

4.3. CSH explorations

To gather in-depth insights into the systemic challenges and potential solutions for energy management in Khorasan Razavi Province, CSH was employed to structure expert interviews. This approach enabled the study to examine multiple dimensions of the energy crisis by engaging a diverse set of stakeholders, including energy experts, environmental scientists, and policy analysts. The interviews were designed around the twelve core CSH questions, which investigate stakeholders, purposes, measures of success, decision-makers, and broader contextual influences (Khazaei et al., 2025b). By focusing on both "as-is" and "ought-to-be" conditions, the interviews facilitated a critical comparison between the current energy system's limitations and its potential ideal state.

Table 2. Summary of CSH results from experts

CSH question	As Is	Ought to be
Who is the client or stakeholder in this system?	Ministry of Oil, Ministry of Energy, industries, and public	Ordinary individuals, organizations, the entire ecosystem, regulators, environmental organizations, and research centers
What is the purpose?	Public satisfaction, energy provision at any cost (e.g., fuel oil)	Provision of clean and sustainable energy, welfare, sustainability, and long-term goals
What is the measure of progress or success?	Expansion of gas and energy supply	Use of clean and renewable energy, sustainable development for all
Who is the decision-maker?	Government, Ministry of Energy, Ministry of Oil, Parliament	Expert groups comprising energy specialists and elite decision-makers
What resources are controlled by the decision-maker?	Fossil fuels and energy resources managed by the Ministry of Oil and Energy	Renewable resources such as wind and solar, laws, and sustainable energy resources

CSH question	As Is	Ought to be
What conditions exist outside the decision environment?	Oil and gas resources, potential environmental resources	International collaboration, technology transfer, and foreign investments
Who is the professional or expert in this system?	Energy experts, governmental specialists	GIS specialists, AI researchers, energy domain scholars
What expertise is required in this system?	Energy domain expertise, extraction, and utilization	Multidisciplinary expertise, AI and data mining, strategic management
Who guarantees the system's success?	Government, Ministry of Energy, and Ministry of Oil	Expert groups, elite professionals, and reliance on renewable resources
Who safeguards the interests of those affected?	Media, city governors, supervisory institutions	Regulatory and oversight organizations with a sustainable community approach
What prevents false promises?	Audit Court, oversight agencies	Transparency, openness, and preventive approaches
What is the defined worldview or vision?	Maximum energy (gas) development	Sustainable energy for all society, environmental protection for future generations

The findings in Table 2 highlight discrepancies between the current state ("As Is") and the desired state ("Ought to be") of the energy system in Khorasan Razavi. While the present framework prioritizes short-term goals such as expanding energy supply and fulfilling immediate needs, the ideal system emphasizes long-term sustainability, public welfare, and environmental preservation. This divergence underscores the need for systemic transformation through multidisciplinary collaboration, the adoption of clean energy technologies, and greater transparency in decision-making processes. One of the key insights from the CSH results is the shift in how stakeholders and clients are defined. The current system identifies government entities and industries as the primary stakeholders, whereas the "Ought to be" vision expands this scope to include individuals, environmental organizations, and research centers. This broader inclusion reflects a commitment to participatory governance and environmental accountability. Similarly, the purpose of the energy system has evolved from merely meeting energy demand to promoting sustainable development and societal well-being.

Table 3 presents actionable strategies to bridge these gaps, categorized into environmental, technological, and societal dimensions. Environmental recommendations, such as transitioning from fossil fuels to renewable energy (S1) and developing sustainable, long-term strategies (S3), align with the CSH vision of prioritizing clean energy and environmental preservation. Technological advancements, including investments in AI-driven optimization (IT2) and the development of clean energy infrastructure (IT3), are essential to achieving operational efficiency and future-proofing the energy sector. In the societal domain, fostering public participation (W2), enhancing energy awareness (W1), and promoting stakeholder collaboration (W3) are pivotal to creating an inclusive and equitable energy system. Strengthening regulatory frameworks (W8) and integrating scientific expertise into decision-making (W7) further support the vision outlined in the CSH analysis. Together, these strategies provide a comprehensive roadmap to address existing shortcomings while paving the way for a sustainable and innovative energy future in Khorasan Razavi.

Table 3. . Strategic improvement options derived from interviews

Society 5.0 category	Code	Option name	Option description
Environmental	S1	Shift Focus from Fossil Fuels to Renewables	Replace fossil fuels with renewable energy sources such as solar and wind to protect the environment and ensure sustainability.
	S2	Increase Use of Renewable Energies	Expand the adoption of modern energy solutions in residential and industrial sectors to reduce environmental impacts.
	S3	Develop Long-term Sustainable Strategies	Focus on sustainable programs and proactive crisis prevention rather than temporary, isolated management.
	S4	Predict and Manage Environmental and Political Risks	Analyze and forecast environmental and political risks and plan for their management to enhance system sustainability.
Technological development	IT1	Invest in Advanced Technologies	Increase investment in advanced technologies to optimize energy production and consumption, reducing reliance on outdated methods.
	IT2	Use Data-driven and AI-based Methods	Leverage data mining and artificial intelligence to optimize energy consumption and forecast future demands.
	IT3	Develop Clean Energy Infrastructure	Build the necessary infrastructure for the production and distribution of renewable energy at the national level.
	IT4	Enhance Oversight Systems and Decision Transparency	Strengthen regulatory institutions and ensure transparency in decision-making processes to prevent systemic errors.
Consumption culture and public participation	W1	Promote Energy Awareness and Behavioral Change	Educate and raise public awareness about energy-efficient consumption and environmental consciousness.
	W2	Strengthen Public Participation Systems	Increase public and NGO involvement in energy and environmental decision-making processes.
	W3	Foster Collaboration Between Public and Private Sectors	Enhance collaboration among ministries, private companies, and academic institutions to improve energy resource utilization.
	W4	Broaden Stakeholders and Clients in the System	Include public participation, environmental organizations, and academic institutions as key stakeholders in the energy system.
	W5	Develop Multidisciplinary and Specialized Human Resources	Train and educate professionals in emerging fields such as AI, data mining, and renewable energy.
	W6	Upgrade Building Standards and Energy Efficiency	Establish new standards for building insulation and improve energy efficiency in industries.
	W7	Strengthen the Role of Scientific and Research Institutions	Enhance the involvement of scientific and research centers in decision-making and the development of innovative energy solutions.
	W8	Optimize Energy Laws and Regulations	Revise energy laws to support clean energy and optimize resource consumption.
	W9	Increased international interactions in the field of energy	Cooperation with leading countries in the field of renewable energy to exchange new knowledge and technologies

4.4. Implementing DANP

The analysis of fuzzy DEMATEL results highlights critical dynamics among the strategies employed for improving the energy system. The prominence measure, calculated as Di+Ri, identifies the most central strategies within the network. Strategies such as IT3 and W3 are most prominent, suggesting they play pivotal roles in achieving system-wide change. IT3, which involves the development of clean energy infrastructure, is particularly essential for transitioning to renewable energy sources and ensuring long-term sustainability. Similarly, W3, focused on fostering collaboration between public and private sectors, emerges as a linchpin for integrating diverse stakeholders into energy decision-making processes.

The net influence metric, Di-Ri, sheds light on the driving and dependent roles of various strategies. Positive values of Di−Ri indicate strategies that are primary drivers within the system. W1, which emphasizes promoting energy awareness and behavioral change, shows a notable driving effect. This strategy's influence underlines the importance of societal shifts in energy consumption patterns to support sustainable energy goals. Similarly, W3 not only shows high prominence but also acts as a driver, highlighting its dual role in shaping and stabilizing the energy system through robust collaboration frameworks. The results of both fuzzy and non-fuzzy DEMATEL analyses are summarized in Table 4. This table presents the computed prominence and relation values for each factor, enabling a comparative interpretation of the two approaches.

Table 4. Output table of fuzzy and non-fuzzy DEMATEL results

	Fuzzy Di			Fuzzy Ri			Fuzzy Di+Ri			Fuzzy Di-Ri			Di+Ri	Di-Ri
	l	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*		
S1	0.5853	1.5899	5.9505	0.5913	1.5930	5.9365	1.1766	3.1829	11.8870	-5.3512	-0.0031	5.3592	4.5514	0.0035
S2	0.6116	1.6086	6.0001	0.5882	1.5971	5.9869	1.1998	3.2057	11.9870	-5.3753	0.0115	5.4119	4.5836	0.0158
S3	0.5504	1.5277	5.9043	0.5978	1.6205	6.0309	1.1482	3.1481	11.9352	-5.4804	-0.0928	5.3065	4.5319	-0.0724
S4	0.5873	1.6080	6.0113	0.6421	1.6861	6.1707	1.2294	3.2941	12.1820	-5.5834	-0.0781	5.3692	4.6743	-0.0697
IT1	0.6049	1.6288	6.0608	0.6387	1.6924	6.1802	1.2436	3.3212	12.2409	-5.5753	-0.0636	5.4221	4.7024	-0.0528
IT2	0.5640	1.5627	5.9159	0.5951	1.5990	5.9693	1.1591	3.1617	11.8852	-5.4053	-0.0364	5.3209	4.5350	-0.0283
IT3	0.6082	1.6403	6.0859	0.6253	1.6827	6.2082	1.2334	3.3230	12.2941	-5.6000	-0.0424	5.4607	4.7100	-0.0390
IT4	0.5987	1.6032	5.9706	0.6069	1.5978	5.9781	1.2056	3.2010	11.9487	-5.3795	0.0054	5.3636	4.5754	0.0049
W1	0.6510	1.7216	6.2234	0.5631	1.5810	5.9824	1.2141	3.3026	12.2058	-5.3314	0.1406	5.6603	4.6819	0.1290
W2	0.5907	1.5897	6.0260	0.5793	1.6071	6.0455	1.1700	3.1968	12.0715	-5.4548	-0.0174	5.4467	4.5867	-0.0067
W3	0.6181	1.6662	6.1934	0.4920	1.3943	5.5757	1.1101	3.0605	11.7691	-4.9576	0.2720	5.7015	4.4440	0.2627
W4	0.5885	1.5892	5.9761	0.5980	1.6345	6.1143	1.1866	3.2237	12.0905	-5.5258	-0.0454	5.3781	4.6094	-0.0421
W5	0.6046	1.6316	6.0983	0.5447	1.5251	5.8762	1.1493	3.1567	11.9745	-5.2715	0.1065	5.5536	4.5435	0.1037
W6	0.5767	1.5865	5.9443	0.6002	1.6064	5.9738	1.1769	3.1929	11.9181	-5.3972	-0.0199	5.3441	4.5628	-0.0146
W7	0.5969	1.5995	5.9418	0.5873	1.6018	6.0801	1.1842	3.2013	12.0219	-5.4833	-0.0023	5.3545	4.5841	-0.0155
W8	0.5889	1.6216	6.0697	0.5623	1.5273	5.8179	1.1512	3.1489	11.8876	-5.2290	0.0944	5.5074	4.5258	0.0966
W9	0.5383	1.4793	5.7416	0.6519	1.7082	6.1872	1.1902	3.1875	11.9289	-5.6490	-0.2289	5.0897	4.5619	-0.2036

Strategies with low or negative Di−Ri values, such as S3 and IT2, are more dependent on other strategies for their success. These strategies rely heavily on the enabling conditions established by stronger drivers like W1 and IT3. For example, the success of IT2, which focuses on leveraging data-driven and AI-based methods, depends significantly on investments in infrastructure (IT3) and awareness campaigns (W1). The interplay between drivers and dependents demonstrates the interconnectedness of strategies and underscores the necessity of a coordinated approach to implementing the energy system transformation. This interconnectedness is further supported by Appendix A, which identifies significant relationships among strategies, highlighting the networked influence among them and emphasizing the need for integrated policy interventions.

Figure 2 presents a causal mapping of strategies by their prominence and influence within the system. The horizontal axis (Di+Ri) indicates the total prominence of a strategy, which combines its overall influence on the system and its dependence within the system. The vertical axis (Di-Ri) reflects the net influence, distinguishing whether a strategy is a driver (positive Di-Ri) or dependent (negative Di-Ri).

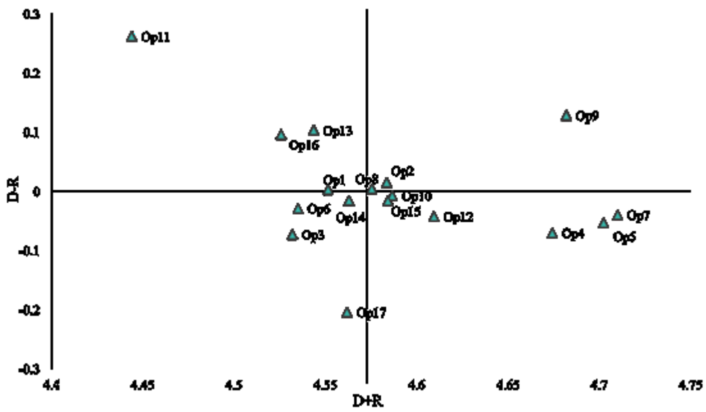

Figure 2. Final diagram of DEMATEL

In the first quadrant, where both prominence and influence are high, the strategies are key drivers of the system. These are the most critical actions to focus on, as they not only significantly impact the system but also have the potential to shape the dynamics of other strategies. They are essential for initiating systemic changes and should be prioritized in planning and resource allocation. The second quadrant, with high prominence but negative influence, includes strategies that are highly interconnected but primarily dependent on other elements. These strategies are vital to the system's functioning but require support from the drivers to be implemented effectively. Addressing these strategies is crucial to ensuring the system's overall stability and operational efficiency. In the third quadrant, where both prominence and influence are low, strategies are peripheral and play a minimal role in driving systemic change. They are supportive and may not require immediate attention unless they enable higher-priority strategies. Meanwhile, the fourth quadrant, characterized by low prominence but positive influence, highlights fewer central strategies that act as influencers. These may not have a broad impact but can trigger specific changes or outcomes within targeted areas of the system. The distribution of strategies across the quadrants provides valuable insights for prioritizing actions and resources. By focusing on the drivers in the first quadrant while supporting dependent strategies in the second, decision-makers can maximize system-wide effectiveness and address key areas of improvement.

According to Table 5, in the environmental strategies category (S), four strategies (S1 to S4) were evaluated, focusing on assessing environmental impacts in the transition from fossil fuels to renewable energy and sustainable development. S2, with an overall score of 0.349158 and a weight of 0.307189, ranked first, highlighting the importance of expanding renewable energy use in environmental strategies. S4, with a score of 0.273584 and a weight of 0.240699, ranked second, emphasizing the management of environmental and political risks. S1 and S3, with weights of 0.232413 and 0.219699, ranked third and fourth, respectively.

Table 5. The weights obtained by DANP

Code	Final score	Rank	Local weight	Local rank
S1	0.264165	16	0.232413	3
S2	0.349158	9	0.307189	1
S3	0.249715	17	0.219699	4
S4	0.273584	15	0.240699	2
IT1	0.274128	14	0.222793	4
IT2	0.304184	12	0.247221	2
IT3	0.297851	13	0.242073	3
IT4	0.354253	6	0.287913	1
W1	0.318347	11	0.099266	9
W2	0.352652	8	0.109962	7
W3	0.358288	5	0.11172	5
W4	0.352843	7	0.110022	6
W5	0.367478	3	0.114586	3
W6	0.366385	4	0.114245	4
W7	0.374455	1	0.116761	1
W8	0.347384	10	0.10832	8
W9	0.369187	2	0.115119	2

In the technological development strategies category (IT), four strategies (IT1 to IT4) were assessed, focusing on investing in advanced technologies, artificial intelligence, and data mining, and developing clean energy infrastructure. IT4, with a score of 0.354253 and a weight of 0.287913, ranked first, underscoring the importance of transparency and the strengthening of monitoring systems for the success of energy systems. IT2, with a score of 0.304184 and a weight of 0.247221, ranked second, emphasizing the use of data-driven methods and artificial intelligence. IT3 and IT1, with relatively similar weights, ranked third and fourth, underscoring the importance of infrastructure development and the optimization of new technologies in the energy sector .In the consumption culture and public participation strategies category (W), the largest category with nine strategies, efforts focus on promoting cultural awareness, strengthening inter-organizational cooperation, and enhancing public participation. W7, with a score of 0.374455 and a weight of 0.116761, ranked first, showing the critical importance of strengthening the role of scientific and research institutions in energy decision-making. W9 and W5, with weights of 0.115119 and 0.114586, ranked second and third, underscoring the importance of optimized laws and regulations in supporting clean energy. These findings indicate that strengthening legal and scientific frameworks is essential for achieving sustainable development. W3 and W4 are also important strategies for fostering interagency collaboration and promoting energy-efficient consumption .Overall, strategies W7, W9, and W5 have the highest scores and weights in this category, underscoring the pivotal role of cultural awareness and public participation, particularly in strengthening scientific institutions and improving regulations, in achieving sustainable development and enhancing energy systems. Additionally, strategies S2 and IT4 are key in their respective categories, focusing on renewable energy development and system transparency. In general, the weights derived from the DANP method highlight the central role of cultural and public participation strategies, particularly in reinforcing scientific institutions and legal improvements. Environmental and technological strategies also rank highly, contributing significantly to the optimization of energy consumption and production (Figure 3).

Figure 3. Diagram of society 5.0 strategies based on CSH

In the analysis of rankings within categories, the results indicate that strategies within each category are prioritized according to their specific importance. In the Environmental category, S2 ranks first with a weight of 0.307189, highlighting the importance of expanding renewable energy development. Additionally, S4, which focuses on managing environmental and political risks, ranks second with a weight of 0.240699, underscoring the importance of long-term planning and risk management for achieving a sustainable system. In the Technological Development category, IT4 ranks first with a weight of 0.287913, emphasizing the critical role of transparency and oversight. This strategy reflects the importance of optimizing and clarifying monitoring systems for managing and utilizing new technologies. Similarly, IT2, with a weight of 0.247221 and a second-place ranking, underscores the importance of leveraging data mining and artificial intelligence for energy consumption optimization.

In the Consumption Culture and Public Participation category, W7 ranks first with a weight of 0.116761, signifying the importance of strengthening scientific and research institutions in energy-related decision-making. W9, with a weight of 0.115119, and W5, with a weight of 0.114586, rank second and third, respectively, indicating the need to improve laws and regulations to promote clean energy consumption and optimize resource use. These rankings highlight that collaboration among governmental, private, and scientific entities, along with cultural promotion, is a key factor in enhancing the energy system and achieving sustainable energy consumption.

5. Discussion

The integration of TSI, CSH, and DANP established a comprehensive and structured framework for analyzing and improving the energy and environmental management system. TSI enabled the exploration of complex systemic challenges through a holistic lens, revealing coordination gaps, policy misalignments, and limited stakeholder participation in Iran's energy governance. It provided the foundation for identifying strategic weaknesses and proposing actionable pathways, especially in renewable energy adoption and environmental risk management. CSH added a reflective and ethical dimension by critically examining the roles, boundaries, and values influencing decision-making. This stage revealed the narrow scope of existing governance, dominated by the Ministry of Energy and the Ministry of Oil, and underscored the need to include scientific institutions, environmental organizations, and independent experts. CSH further redefined the perspective from "energy at any cost" toward "clean and sustainable energy," promoting long-term, knowledge-based, and participatory governance reforms to enhance transparency and resilience in energy planning.

Building on these qualitative insights, the fuzzy DEMATEL–ANP analysis quantified the interrelations and priorities among identified strategies. The results highlighted the most influential factors driving sustainability and system transformation, such as strengthening scientific and research institutions (W7), optimizing energy laws and regulations (W9), enhancing multidisciplinary human resource development (W5), improving transparency and oversight systems (IT4), and expanding renewable energy adoption (S2). These high-ranking strategies formed the analytical foundation of the E-FLEX 5.0 model, confirming the pivotal role of research, regulation, and innovation in shaping a participatory and technologically adaptive energy transition. The findings underscore the importance of coordinated investment in clean energy infrastructure, stronger institutional collaboration, and the adoption of digital technologies such as AI and data mining to improve forecasting and policy integration. Overall, the results provide a clear, empirically grounded roadmap for implementing participatory, technology-driven, and sustainability-oriented energy governance.

5.1. The final E-FLEX 5.0 model

The E-FLEX 5.0 model serves as a comprehensive, flexible, and dynamic framework for policymaking and action research in the fields of energy and sustainable development (Figure 4). This model is built on a core participatory methodology, engaging various stakeholders across phases and employing systems thinking tools and modern methodologies. In the initial methodological phase, a collaborative effort with experts involves conducting statistical analyses and a comprehensive evaluation of the current situation, particularly from the perspective of territorial planning. This phase aims to thoroughly identify the existing conditions, challenges, and potential opportunities. Based on expert opinions and analyses, a detailed framework of fundamental issues and essential needs is developed, paving the way for subsequent phases. The second step of the E-FLEX 5.0 methodology core employs an action research approach. At this stage, systemic methodologies, such as TSI, and complementary methods, such as CSH, are applied. These approaches assist the implementation team in fully understanding complex organizational and societal issues and developing appropriate solutions. Active stakeholder engagement is fostered through the action research process, with CSH serving as the primary tool for critical analysis and issue clarification. This ensures that stakeholders gain a precise understanding of the topics addressed and the changes required to current systems.

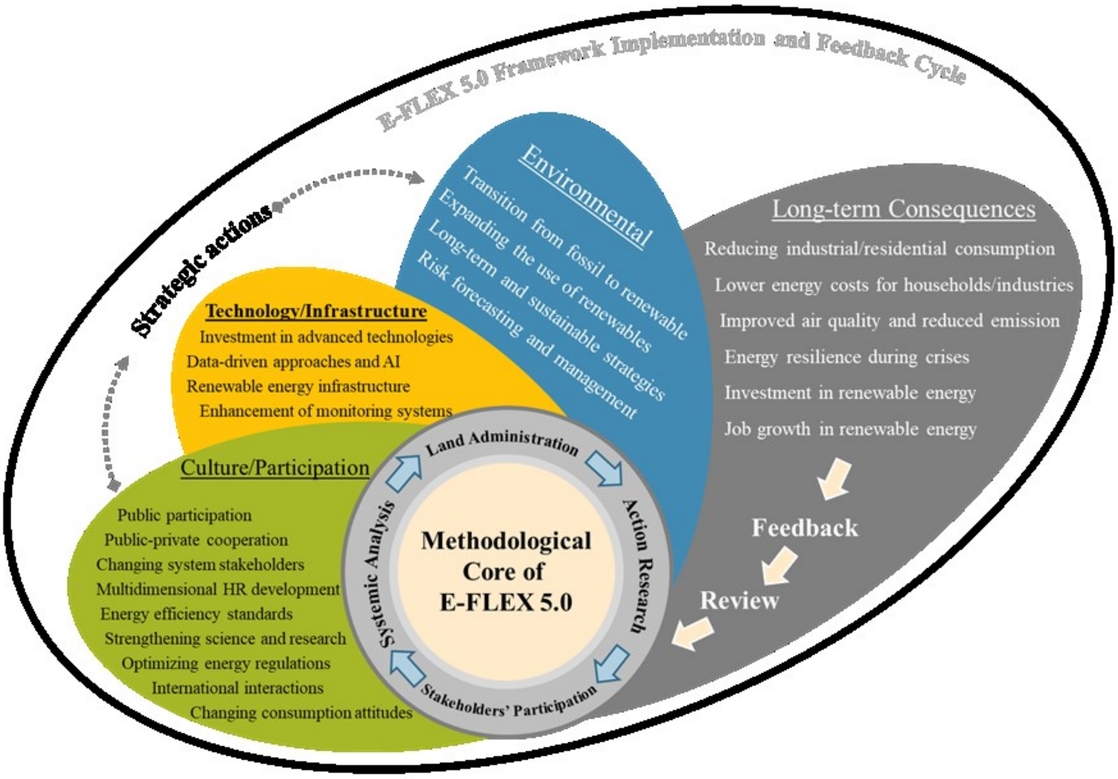

Figure 4. E-FLEX 5.0 model framework, methodological, and implementation core

The third and fourth steps of the EFLEX 5.0 model focus on ranking and prioritizing options. Following action research and a detailed stakeholder analysis, various options are evaluated with stakeholder participation. These options are ranked based on strategies such as sustainability, efficiency, and impact. This ranking helps the implementation team structure operational plans in a phased manner, aligned with strategic priorities. Analytical tools like DANP are employed for priority assessment, alongside critical insights and expertise from specialists, ensuring well-informed final decisions. The second phase includes implementing strategic actions categorized into three broad areas: environmental, technological and infrastructural, and public participation and cultural change. Environmental actions aim to enhance renewable energy use, manage natural resources, and reduce environmental impacts. Technological and infrastructural actions emphasize investing in advanced technologies, building clean energy infrastructure, and developing data-driven systems. Actions related to public participation and culture focus on changing societal attitudes toward energy consumption and fostering cooperation among the government, the private sector, and the public. Collectively, these strategies contribute to sustainable development and reduce dependence on fossil fuels.

Following the implementation of these strategic actions, the EFLEX 5.0 model enters its third phase, which involves assessing and reviewing outcomes. It is anticipated that these actions will have tangible and long-term impacts on energy and sustainable development. Expected outcomes include improved quality of life, reduced environmental pollution, enhanced energy efficiency, and strengthened technological infrastructure. Regular, continuous evaluations will ensure that expected results are achieved and that necessary adjustments are made promptly. A key feature of the EFLEX 5.0 model is its emphasis on continuous review and improvement. Periodic assessments and feedback from different stages of implementation support optimization and alignment with environmental and social changes. Designed as a long-term participatory model, EFLEX 5.0 remains adaptable to future societal needs and can be redesigned with each implementation cycle to meet emerging challenges and conditions.

5.2. Predicted outcomes

Ultimately, EFLEX 5.0 serves as a dynamic framework for policymakers and decision-makers to systematically and strategically address complex energy and environmental challenges. By leveraging modern systemic methodologies, the model fosters innovation and continuous improvement, thereby enabling replication in other regions and countries. For energy consumption in Razavi Khorasan Province, six tangible outcomes are anticipated based on implementing renewable energy strategies and reducing reliance on fossil fuels:

- By shifting focus to renewable energies, the reliance on natural gas as the primary energy source in Razavi Khorasan Province will decrease, leading to reduced usage in both industrial and residential sectors.
- Data-driven and AI-based optimization methods will lower energy consumption, resulting in reduced gas costs, particularly benefiting gas-dependent industries.
- Increased adoption of renewable energies and reduced gas usage will significantly decrease pollution from fossil fuels, improving air quality in cities like Mashhad, which faces severe pollution issues.
- By replacing natural gas with renewable energy and managing risks, Razavi Khorasan Province will achieve greater energy security, reducing vulnerability to gas price fluctuations and crises.
- Investments in modern technologies and clean energy infrastructure will expand renewable energy projects, such as wind and solar, strengthening the province's new energy sector.
- Long-term sustainable energy strategies will create new employment opportunities in areas like installation and operation of renewable energy infrastructure, boosting the job market and reducing unemployment in Razavi Khorasan Province.

6. Conclusion

Before presenting the main findings, it is worth clarifying how the results were derived. The methodological process combined systemic diagnosis with quantitative prioritization. Expert input was systematically analyzed to identify causal links and assign weights to strategies under the Society 5.0 framework. This integration of qualitative stakeholder assessment and quantitative modeling ensured that the results reflect both human-centered perspectives and data-driven rigor. The findings of this study highlight the importance of a participatory and systemic approach to addressing the energy challenges faced by Razavi Khorasan Province. By employing TSI, CSH, and the DANP method, this research provides a comprehensive framework for prioritizing strategies that balance environmental sustainability, technological advancements, and cultural shifts. The results emphasize the need to transition from fossil fuels to renewable energy, to invest in modern technologies such as AI and data-driven systems, and to strengthen the role of scientific and regulatory institutions. These strategies collectively enable sustainable development, reduce dependence on natural gas, and improve environmental outcomes.

The insights gained from this study are highly relevant to other regions and contexts, particularly those facing similar energy crises. The integration of systemic methodologies, such as TSI and CSH, enabled a deeper understanding of the complex interdependencies among stakeholders, resources, and strategies. Moreover, the DANP analysis demonstrated that prioritizing key strategies such as clean energy infrastructure (IT3) and public collaboration (W3) can have transformative effects. The study also underscored the importance of fostering inclusivity by engaging diverse stakeholders, ranging from policymakers to local communities, in the decision-making process. These findings highlight the critical need for a holistic approach to energy governance that aligns with both short-term needs and long-term sustainability goals.

Future implications of this research extend beyond the energy sector. The proposed E-FLEX 5.0 framework offers a replicable model for addressing systemic challenges across domains such as urban planning, water resource management, and climate change mitigation. The emphasis on stakeholder engagement and continuous evaluation ensures adaptability to evolving conditions and emerging technologies. As global energy transitions accelerate, the findings of this study can guide policymakers and practitioners in implementing participatory, data-driven, and sustainable solutions to address energy and environmental challenges in both regional and global contexts. By fostering innovation and collaboration, this research contributes to the development of resilient systems capable of meeting the demands of the Society 5.0 vision.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Abdolahinia, H., Heidarizadeh, M. and Rahmati, I., 2024. Assessing Iran and its neighbors for prospects and challenges: The case of the electrical sector. *Renewable and Sustainable Energy Reviews, 193*, p.114190. https://doi.org/10.2139/ssrn.4480019.

Adel, A. and Alani, N. H., 2024. Human-Centric Collaboration and Industry 5.0 Framework in Smart Cities and Communities: Fostering Sustainable Development Goals 3, 4, 9, and 11 in Society 5.0. *Smart Cities, 7*, p.1723 https://doi.org/10.3390/smartcities7040068.

Ardakani, D. A., Kiani, M. and Babakhanifard, M. S., 2024. A Fuzzy DEMATEL-FCM approach for analyzing the enablers of the circular economy and Industry 4.0 in the supply chain. *Corporate Social Responsibility and Environmental Management, 31*, pp.5574-5589.

Bonakdari, H., Khazaei, M., Gholian-Jouybari, F. and Hajiaghaei-Keshteli, M., 2025. Sustainable wastewater-to-hydrogen systems in Canada: A scenario-based decision support analysis. *Renewable Energy*, p.124308 https://doi.org/10.1016/j.renene.2025.124308.

Chen, S.-H. and Lin, W.-T., 2018. Analyzing determinants for promoting emerging technology through intermediaries by using a DANP-based MCDA framework. *Technological Forecasting and Social Change, 131*, pp.94-110. https://doi.org/10.1016/j.techfore.2017.09.019.

Deguchi, A., Hirai, C., Matsuoka, H., Nakano, T., Oshima, K., TAI, M. and TANI, S., 2020. What is society 5.0. *Society, 5*, pp.1-24.

Dehghan Nayeri, M., Khazaei, M. and Alinasab-Imani, F., 2020. The critical heuristics of iranian banking credit system: analysis of the antithetical opinions of the beneficiaries. *Systemic Practice and Action Research, 33*, pp.363-392. https://doi.org/10.1007/s11213-020-09524-x.

Ebrahimi, S., Fathi, M. R. and Shahbazi, M., 2025. Critical Systems Heuristics for Sustainable Management of Iran's Water-Energy-Food Nexus. *Journal of Systems Thinking in Practice, 4*, pp.82-108. https://doi.org/10.22067/jstinp.2025.91072.1130.

Ehsanifar, M., Dekamini, F., Spulbar, C., Birau, R., Khazaei, M. and Bărbăcioru, I. C., 2023. A Sustainable Pattern of Waste Management and Energy Efficiency in Smart Homes Using the Internet of Things (IoT). *Sustainability, 15*, p.5081 https://doi.org/10.3390/su15065081.

Emrouznejad, A. and Marra, M., 2017. The state of the art development of AHP (1979–2017): A literature review with a social network analysis. *International journal of production research, 55*, pp.6653-6675. https://doi.org/10.1080/00207543.2017.1334976.

Estévez, R. A., Espinoza, V., Ponce Oliva, R. D., Vásquez-Lavín, F. and Gelcich, S., 2021. Multi-criteria decision analysis for renewable energies: research trends, gaps and the challenge of improving participation. *Sustainability, 13*, p.3515. https://doi.org/10.3390/su13063515.

Foukolaei, P. Z., Asari, F. A., Khazaei, M., Gholian-Jouybari, F. and Hajiaghaei-Keshteli, M., 2024. From responsible sourcing of wastes to sustainable energy consumption in the blue hydrogen supply chain: Case of nearshoring in Nuevo Leon. *International Journal of Hydrogen Energy, 77*, pp.1387-1400. https://doi.org/10.1016/j.ijhydene.2024.06.079.

Galende-Sánchez, E. and Sorman, A. H., 2021. From consultation toward co-production in science and policy: A critical systematic review of participatory climate and energy initiatives. *Energy Research & Social Science, 73*, p.101907 https://doi.org/10.1016/j.erss.2020.101907.

Ghaedi, M., Foukolaei, P. Z., Asari, F. A., Khazaei, M., Gholian-Jouybari, F. and Hajiaghaei-Keshteli, M. 2024. Pricing electricity from blue hydrogen to mitigate the energy rebound effect: A case study in agriculture and livestock. *International Journal of Hydrogen Energy, 84*, pp.993-1003. https://doi.org/10.1016/j.ijhydene.2024.08.241.

Ghobakhloo, M., Iranmanesh, M., Fathi, M., Rejeb, A., Foroughi, B. and Nikbin, D., 2024. Beyond Industry 4.0: a systematic review of Industry 5.0 technologies and implications for social, environmental and economic sustainability. *Asia-Pacific Journal of Business Administration*. Advance online publication. https://doi.org0.1108/APJBA-09-2023-0447.

Gholian-Jouybari, F., Khazaei, M., Saen, R. F., KIA, R., Bonakdari, H., Hajiaghaei-Keshteli, M. and Ramezani, M., 2024. Developing environmental, social and governance (ESG) strategies on evaluation of municipal waste disposal centers: A case of Mexico. *Chemosphere, 364*, p.142961. https://doi.org/10.1016/j.chemosphere.2024.142961.

Gölcük, İ. and Baykasoğlu, A., 2016. An analysis of DEMATEL approaches for criteria interaction handling within ANP. *Expert Systems with Applications, 46*, pp.346-366. https://doi.org/10.1016/j.eswa.2015.10.041.

Gössling, S., Balas, M., Mayer, M. and Sun, Y.-Y. 2023. A review of tourism and climate change mitigation: The scales, scopes, stakeholders and strategies of carbon management. *Tourism Management, 95*, p.104681. https://doi.org/10.1016/j.tourman.2022.104681.

Hanke, F., Guyet, R. and Feenstra, M., 2021. Do renewable energy communities deliver energy justice? Exploring insights from 71 European cases. *Energy Research & Social Science, 80*, p.102244. https://doi.org/10.1016/j.erss.2021.102244.

Hasheminezhad, A., Hadadi, F. and Shirmohammadi, H., 2021. Investigation and prioritization of risk factors in the collision of two passenger trains based on fuzzy COPRAS and fuzzy DEMATEL methods. *Soft Computing, 25*, pp.4677-4697. https://doi.org/10.1007/s00500-020-05478-3.

Heidari, H., Akbari, M., Souhankar, A. and Hafezi, R., 2022. Review of global energy trends towards 2040 and recommendations for Iran oil and gas sector. *International Journal of Environmental Science and Technology, 19*, pp.8007-8018. https://doi.org/10.1007/s13762-022-03963-w.

Hsu, C.-C., Liou, J. J. and Chuang, Y.-C., 2013. Integrating DANP and modified grey relation theory for the selection of an outsourcing provider. *Expert systems with applications, 40***,** pp.2297-2304. https://doi.org/10.1016/j.eswa.2012.10.040.

Hussain, S. A., Razi, F., Hewage, K. and Sadiq, R., 2023. The perspective of energy poverty and 1st energy crisis of green transition. *Energy, 275***,** p.127487. https://doi.org/10.1016/j.energy.2023.127487.

Jamali, M., Soufizadeh, S., Yeganeh, B. and Emam, Y., 2021. A comparative study of irrigation techniques for energy flow and greenhouse gas (GHG) emissions in wheat agroecosystems under contrasting environments in south of Iran. *Renewable and Sustainable Energy Reviews, 139***,** p.110704. https://doi.org/10.1016/j.rser.2021.110704.

Ju, Y., Wang, A. and You, T., 2015. Emergency alternative evaluation and selection based on ANP, DEMATEL, and TL-TOPSIS. *Natural Hazards, 75***,** pp.347-379. https://doi.org/10.1007/s11069-014-1077-8.

Kadoić, N., Divjak, B. and Begičević Ređep, N., 2019. Integrating the DEMATEL with the analytic network process for effective decision-making. *Central European Journal of Operations Research, 27***,** pp.653-678. https://doi.org/10.1007/s10100-018-0601-4.

Keskar, A., Galik, C. and Johnson, J. X., 2023. Planning for winter peaking power systems in the United States. *Energy Policy, 173***,** p.113376. https://doi.org/10.1016/j.enpol.2022.113376.

Khan, M. I., 2017. Falling oil prices: Causes, consequences and policy implications. *Journal of Petroleum Science and Engineering, 149***,** pp.409-427. https://doi.org/10.1016/j.petrol.2016.10.048.

Khazaei, M., Gholian-Jouybari, F., Dolatabadi, M. D., Alamdari, A. P., Eskandari, H. and Hajiaghaei-Keshteli, M., 2025a. Renewable energy portfolio in Mexico for Industry 5.0 and SDGs: Hydrogen, wind, or solar? *Renewable and Sustainable Energy Reviews, 213***,** p.115420. https://doi.org/10.1016/j.rser.2025.115420.

Khazaei, M., Gholian-jouybari, F., Ramezani, M. and Hajiaghaei-Keshteli, M., 2025b. Environmental, social, and governance enablers of the hydrogen supply chain: Application of community operational research using STRIDES framework. *Journal of Environmental Management, 389***,** p.126092. https://doi.org/10.1016/j.jenvman.2025.126092.

Khazaei, M., Hajiaghaei-Keshteli, M., Rajabzadeh Ghatari, A., Ramezani, M., Fooladvand, A. and Azar, A., 2023. A multi-criteria supplier evaluation and selection model without reducing the level of optimality. *Soft Computing***,** pp.1-14. https://doi.org/10.1007/s00500-023-08954-8.

Khazaei, M., Ramezani, M., Padash, A. & Detombe, D., 2021a. Creating shared value to redesigning IT-service products using SYRCS; Diagnosing and tackling complex problems. *Information Systems and e-Business Management, 19***,** pp.957-992. https://doi.org/10.1007/s10257-021-00525-4.

Khazaei, M., Ramezani, M., Padash, A. and Detombe, D., 2021b. The quantification role of BWM in problem structuring methods: SYRCS methodology. the international workshop on best-worst method, 2021b. Springer, pp.252-271. https://doi.org/10.1007/978-3-030-89795-6_18.

Lambert, L. A., Tayah, J., Lee-Schmid, C., Abdalla, M., Abdallah, I., ALI, A. H., Esmail, S. and Ahmed, W., 2022. The EU's natural gas Cold War and diversification challenges. *Energy Strategy Reviews, 43*, p.100934. https://doi.org/10.1016/j.esr.2022.100934.

Liu, G., Dong, X., Kong, Z., Jiang, Q. and Li, J., 2021. The role of China in the East Asian natural gas premium. *Energy Strategy Reviews, 33*, p.100610. https://doi.org/10.1016/j.esr.2020.100610.

Midgley, G. and Rajagopalan, R., 2020. Critical systems thinking, systemic intervention, and beyond. *Handbook of systems sciences*, pp.1-51. https://doi.org/10.1007/978-981-13-0370-8_7-1.

Mohaghar, A., Taghizadeh Yazdi, M. R., Maleki, M. H. and Mansouri, S., 2025. Designing an Agricultural Biomass Supply Chain Model Using Cross Impact Analysis. *Journal of Systems Thinking in Practice*, *4*(4), pp.1-26. https://doi.org/10.22067/jstinp.2025.94846.1171.

Nakamura, T. and Kijima, K., 2011. Total system intervention for system failures and its application to information and communication technology systems. *Systems Research and Behavioral Science, 28*, pp.553-566. https://doi.org/10.1002/sres.1114.

Nasrollahi, M., Fathi, M. R., Sobhani, S. M., Khosravi, A. and Noorbakhsh, A., 2023. Modeling resilient supplier selection criteria in desalination supply chain based on fuzzy DEMATEL and ISM. *Sustainable logistics systems using ai-based meta-heuristics approaches.* Routledge.

Nath, S., Shams, J., Van Laerhoven, F. and Driessen, P., 2022. The impact of decision-making on conflict: Rethinking the roles of technocrats and residents during Tidal River Management in coastal Bangladesh. *Land Use Policy, 117*, p.106103. https://doi.org/10.1016/j.landusepol.2022.106103.

Noorollahi, Y., Lund, H., Nielsen, S. and Thellufsen, J. Z., 2021. Energy transition in petroleum rich nations: Case study of Iran. *Smart Energy, 3*, p.100026. https://doi.org/10.1016/j.segy.2021.100026.

Pamučar, D., Behzad, M., Božanić, D. and Behzad, M., 2021. Decision making to support sustainable energy policies corresponding to agriculture sector: Case study in Iran's Caspian Sea coastline. *Journal of Cleaner Production, 292*, p.125302. https://doi.org/10.1016/j.jclepro.2020.125302.

Peng, H.-G. and Wang, J.-Q., 2018. A multicriteria group decision-making method based on the normal cloud model with Zadeh's Z-numbers. *IEEE transactions on Fuzzy Systems, 26*, pp.3246-3260. https://doi.org/10.1109/tfuzz.2018.2816909.

Ramezani, M., Azar, A. & Khazaei, M., 2021. Gap analysis through a hybrid method: Critical systems heuristics and best worst method. *The International Workshop on Best-Worst Method.* Springer, pp.272-286. https://doi.org/10.1007/978-3-030-89795-6_19.

Saaty, T. L., 2004. Fundamentals of the analytic network process—multiple networks with benefits, costs, opportunities and risks. *journal of systems science and systems engineering, 13*, pp.348-379. https://doi.org/10.1007/s11518-006-0171-1.

Slocum, A. H. and Gessel, D. J., 2022. Evolving from a hydrocarbon-based to a sustainable economy: Starting with a case study for Iran. *Renewable and Sustainable Energy Reviews, 154*, p.111750. https://doi.org/10.1016/j.rser.2021.111750.

Solaymani, S., 2021. A review on energy and renewable energy policies in Iran. *Sustainability, 13*, p.7328. https://doi.org/10.3390/su13137328.

Sorourkhah, A. and Edalatpanah, S., 2022. Using a combination of matrix approach to robustness analysis (MARA) and fuzzy DEMATEL-based ANP (FDANP) to choose the best decision. *International journal of mathematical, engineering and management sciences, 7*, p.68. https://doi.org/10.33889/ijmems.2022.7.1.005.

Spyridonidou, S., Sismani, G., Loukogeorgaki, E., Vagiona, D. G., Ulanovsky, H. and Madar, D., 2021. Sustainable spatial energy planning of large-scale wind and PV farms in Israel: A collaborative and participatory planning approach. *Energies,* pp.14, 551. https://doi.org/10.3390/en14030551.

Stadelmann-Steffen, I. and Dermont, C., 2021. Acceptance through inclusion? Political and economic participation and the acceptance of local renewable energy projects in Switzerland. *Energy research & social science, 71*, p.101818. https://doi.org/10.1016/j.erss.2020.101818.

Stober, D., Suškevičs, M., Eiter, S., Müller, S., Martinát, S. and Buchecker, M., 2021. What is the quality of participatory renewable energy planning in Europe? A comparative analysis of innovative practices in 25 projects. *Energy Research & Social Science, 71*, p.101804. https://doi.org/10.1016/j.erss.2020.101804.

Taghipour, A., Foukolaei, P. Z., Ghaedi, M. and Khazaei, M., 2023. Sustainable Multi-Objective Models for Waste-to-Energy and Waste Separation Site Selection. *Sustainability, 15*, p.15764. https://doi.org/10.3390/su152215764.

Taghipour, A., Padash, A., Etemadi, V., Khazaei, M. and Ebrahimi, S., 2024. Sustainable and Circular Hotels and the Water–Food–Energy Nexus: Integration of Agrivoltaics, Hydropower, Solar Cells, Water Reservoirs, and Green Roofs. *Sustainability, 16*, p.1985. https://doi.org/10.3390/su16051985.

Taghvaee, V. M., Arani, A. A., Soretz, S. and Agheli, L., 2022. Comparing energy efficiency and price policy from a sustainable development perspective: Using fossil fuel demand elasticities in Iran. *MRS Energy & Sustainability, 9*, pp.480-493. https://doi.org/10.1557/s43581-022-00024-0.

Tang, J. W. and Tsai, P. H., 2024. An Empirical Study of Sustainable Development Model for Recreational Fishery Based on Multiple Perspectives. *International Journal of Tourism Research, 26*, p.e2754. https://doi.org/10.1002/jtr.2754.

Tayebi, M., Bemani, A., Fetanat, A. and Fehresti-Sani, M., 2022. A decision support system for sustainability prioritization of air pollution control technologies in energy and carbon management: Oil & gas industry of Iran. *Journal of Natural Gas Science and Engineering, 99*, p.104416. https://doi.org/10.1016/j.jngse.2022.104416.

Tickner, J., Geiser, K. and Baima, S., 2021. Transitioning the chemical industry: the case for addressing the climate, toxics, and plastics crises. *Environment: Science and Policy for Sustainable Development, 63*, pp.4-15. https://doi.org/10.1080/00139157.2021.1979857.

Torlak, G. N., 2001. Reflections on multimethodology: Maximizing flexibility, responsiveness, and sustainability in multimethodology interventions through a theoretically and practically improved version of total systems intervention (TSI). *Systemic Practice and Action Research, 14*, pp.297-337. https://doi.org/10.1023/a:1011359315360.

Van de Graaf, T., 2023. The geopolitics of energy after Russia's war in Ukraine. *Forging Europe's leadership: Global trends, Russian aggression and the risk of a regressive world Ukraine World.* Foundation for European Progressive Studies. Available at: https://feps-europe.eu/publication/forging-europes-leadership/.

Wahlund, M. and Palm, J., 2022. The role of energy democracy and energy citizenship for participatory energy transitions: A comprehensive review. *Energy Research & Social Science, 87*, p.102482. https://doi.org/10.1016/j.erss.2021.102482.

Wu, K.-J., Chen, Q., Qi, Y., Jiang, X., Gao, S. and Tseng, M.-L., 2019. Sustainable development performance for small and medium enterprises using a fuzzy synthetic method-DEMATEL. *Sustainability, 11*, p.4119. https://doi.org/10.3390/su11154119.

World Economic Forum, 2024. *Global gas consumption and growth rate*. World Economic Forum. Available at: https://www.weforum.org/ (Accessed: 04 October 2026).

Yu, Z., Razzaq, A., Rehman, A., Shah, A., Jameel, K. and Mor, R. S., 2021. Disruption in global supply chain and socio-economic shocks: a lesson from COVID-19 for sustainable production and consumption. *Operations Management Research*, pp.1-16. https://doi.org/10.1007/s12063-021-00179-y.

Zahedi, R., Zahedi, A. and Ahmadi, A., 2022. Strategic study for renewable energy policy, optimizations and sustainability in Iran. *Sustainability, 14*, p.2418. https://doi.org/10.3390/su14042418.

Zhou, Y. and Lund, P. D., 2023. Peer-to-peer energy sharing and trading of renewable energy in smart communities─ trading pricing models, decision-making and agent-based collaboration. *Renewable Energy, 207*, pp.177-193. https://doi.org/10.1016/j.renene.2023.02.125.

Appendices

Appendix A. Significant relationships between strategies (cells with values of 1)

	S1	S2	S3	S4	IT1	IT2	IT3	IT4	W1	W2	W3	W4	W5	W6	W7	W8	W9
S1	0	1	1	1	1	0	0	1	1	0	0	0	1	1	1	0	1
S2	1	0	1	1	0	1	1	0	1	1	0	1	0	1	1	0	1
S3	0	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0	1
S4	1	0	1	0	1	0	1	1	1	1	0	0	0	0	0	0	1
IT1	1	1	0	1	0	1	1	1	1	1	0	1	1	1	0	1	1
IT2	1	1	0	1	1	0	1	0	0	1	0	1	0	0	0	1	1
IT3	1	0	1	1	1	1	0	1	0	0	0	1	1	0	0	1	1
IT4	1	1	1	0	1	1	1	0	0	1	0	1	0	0	1	1	1
W1	0	1	1	1	1	1	1	1	0	1	0	1	1	1	1	0	1
W2	0	1	1	1	1	1	0	0	1	0	0	1	1	1	1	0	1
W3	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
W4	0	0	0	1	1	1	1	1	0	1	0	0	0	1	0	0	1
W5	0	1	0	1	1	1	1	1	0	1	0	1	0	1	1	0	1
W6	0	0	1	1	0	0	1	1	0	1	0	1	0	0	1	1	0
W7	1	1	1	1	1	1	1	0	0	1	0	1	0	1	0	0	1
W8	0	1	1	1	1	0	1	1	1	0	0	1	1	1	1	0	1
W9	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0