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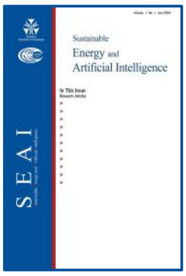

Futures of AI in Climate-Responsive Energy Systems: A Scenario-Based Approach

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Abstract

Climate change has significantly reshaped energy supply and demand by increasing the frequency and severity of extreme events, thereby intensifying challenges related to the sustainability and security of energy systems. In response, artificial intelligence (AI) has emerged as a critical enabling technology with the potential to improve forecasting accuracy, operational flexibility, and system resilience under non-stationary climatic conditions. Nevertheless, the future integration of AI into energy systems is subject to profound uncertainties arising from climatic dynamics, governance structures, and policy environments. This study investigates plausible futures of AI-enabled climate-responsive energy systems in Iran through a scenario-based approach. The research adopts an applied mixed-methods design. Initially, key drivers influencing the future development of climate-responsive energy systems were identified through a systematic literature review and expert interviews. Subsequently, Cross-Impact Analysis using the MICMAC method was employed to examine the influence–dependence relationships among these drivers. The analysis identified climate and energy security pressures and environmental and market-based policy stringency as the dominant exogenous drivers shaping system evolution. Based on the alternative states of these two critical uncertainties, four plausible future scenarios were constructed. The results indicate that under high climate pressure, strong and coherent governance combined with market-oriented environmental policies can convert stress into a driver of structural transformation and systematic AI deployment. Conversely, weak policy frameworks even when climate pressures are moderate lead to missed opportunities and the accumulation of long-term vulnerabilities. Overall, the study highlights that managing uncertainty through effective governance and strategic AI adoption is central to achieving resilient energy futures in Iran.

Keywords: Artificial intelligence; Climate change; Climate-responsive energy systems; Futures studies; Scenario analysis; Cross-Impact Analysis (MICMAC); Energy security; Energy governance; Iran.

1. Introduction

Climate change is reshaping both the temporal patterns and the magnitudes of energy supply and demand, creating new forms of instability that place increasing stress on existing energy systems. Extreme heat waves, altered wind and solar resource distributions, shifting precipitation regimes, and changing patterns of heating and cooling demand collectively increase the frequency, amplitude, and geographic heterogeneity of supply–demand mismatches. Research demonstrates that climate-driven shifts in renewable resource availability and demand-side loads can substantially reduce local supply–demand match (SDM) across large land areas, with strong regional variation and non-linear effects on overall system performance (Liu et al., 2023). Climate change alters the spatial and temporal distribution of wind speed, solar irradiance, and hydrological inputs, with multi-model assessments identifying robust reductions in SDM in many mid-to-high latitude regions due to smaller or more variable wind and solar supply, while some low-latitude regions may experience increased mean renewable supply accompanied by elevated cooling-driven demand, thereby amplifying net system stress (Liu et al., 2023). Changes in precipitation and runoff further reduce hydropower reliability, while higher water temperatures and increased water scarcity constrain thermal power plant cooling and generation capacity. In parallel, shifts in the seasonality of wind and solar resources increasingly desynchronize supply profiles from traditional demand peaks, such as winter heating and summer cooling, exacerbating supply–demand mismatches.

On the demand side, rising average temperatures and more frequent heat extremes intensify cooling demand, while milder winters may reduce heating demand in some regions; however, the net effect often manifests as higher and more volatile peak loads during heatwaves. Extreme weather events such as heatwaves and cold snaps introduce non-stationarity into electricity demand, generating short-term demand spikes that are both more frequent and less predictable than historical baselines. Climate-induced stress on water resources and agricultural systems further feeds back into energy demand through increased requirements for irrigation pumping, desalination, and cooling, complicating demand forecasting and system planning. These dynamics are often compounded by cascading risks, where the coincidence of supply shocks and demand peaks such as heatwaves that simultaneously reduce photovoltaic efficiency while driving air-conditioning loads amplifies system vulnerability. Climate impacts on transmission infrastructure, including fires, floods, and storms, degrade delivery capacity and render localized supply–demand imbalances more consequential, while failures across interconnected infrastructures can trigger non-linear system responses and widespread blackouts.

Despite these escalating challenges, traditional energy systems are structurally limited in their capacity to respond effectively to climate-induced shocks. Conventional systems are highly centralized and optimized for historical, relatively stationary resource and demand patterns, and both physical and institutional inertia manifested in long lead times for generation and grid upgrades impede rapid structural adaptation. Long asset lifetimes and extended planning horizons further constrain the ability of these systems to reconfigure swiftly in response to evolving climate realities. At the operational level, conventional grid management relies heavily on deterministic or simplified stochastic forecasts and often lacks sensitivity to emerging climatic non-stationarity, while many legacy systems remain deficient in high-resolution sensing and data architectures necessary for real-time situational awareness. Control and market mechanisms have historically been designed around dispatchable and predictable generation within vertically integrated control hierarchies, rendering them poorly suited to accommodating high penetrations of distributed and variable renewables, behind-the-meter resources, and flexible demand. In addition, physical flexibility in the form of fast-ramping generation, storage capacity, and distributed resources is frequently insufficient, and prevailing market and regulatory structures have tended to under-incentivize distributed flexibility and demand response, thereby reducing adaptive capacity during climate-induced shocks. Vulnerabilities in fuel supply chains, cooling water availability, and maintenance services during extreme weather events further expose brittle dependencies that traditional energy architectures are ill-equipped to manage.

Against this backdrop, artificial intelligence (AI) offers a set of technological capabilities that, while not a panacea, can materially enhance the climate-responsiveness, adaptivity, and resilience of energy systems. These capabilities can be broadly grouped into the domains of prediction, optimization, and self-regulation. In the domain of prediction, machine learning models, when integrated with physical climate models and multi-source observational data such as satellite imagery, remote sensing, and distributed sensors, can deliver high-resolution probabilistic forecasts of renewable generation, electricity demand, and grid stressors under non-stationary climate conditions. Such advances improve lead times for both operational and market decisions. Deep learning techniques applied to dense meteorological and sensor data can also support nowcasting and early detection of extreme events, including convective storms and rapid temperature increases, enabling pre-emptive operational responses and targeted emergency dispatch. Moreover, generative and surrogate modeling approaches can emulate complex climate–infrastructure interactions far more rapidly than full physics-based models, facilitating extensive Monte Carlo scenario exploration for planning and risk assessment.

In terms of optimization, AI-driven methods such as reinforcement learning and stochastic programming augmented with machine-learning surrogates can support the scheduling of distributed energy resources, storage systems, and demand-response portfolios under probabilistic climate forecasts, thereby maximizing reliability and minimizing costs in the presence of deep uncertainty. Evolutionary and constrained optimization techniques further enable the explicit negotiation of tradeoffs among resilience, cost, emissions, and social objectives dimensions often neglected in deterministic optimization frameworks. AI also enables co-optimization across interconnected sectors, allowing coordinated management of energy–water–food interactions, such as aligning desalination schedules with photovoltaic availability, an approach increasingly recognized as necessary in systems where multiple resource domains interact under climate stress (Dlamini et al., 2024; Zhang et al., 2025). In the domain of self-regulation, distributed machine-learning agents deployed on edge devices, including smart inverters and microgrid controllers, can perform local balancing, islanding, and cooperative control to maintain system stability when centralized control is compromised. Online learning systems can adapt protection settings in response to anomalous grid behavior induced by climate events, limiting fault propagation, while AI-mediated demand-response platforms can orchestrate large populations of flexible loads, such as electric vehicles and thermostatically controlled devices, reshaping demand profiles in near real time with minimal consumer friction. Predictive analytics further support proactive maintenance scheduling and logistics optimization, mitigating climate-exacerbated failures and supply-chain disruptions.

Notwithstanding these opportunities, significant limitations, risks, and governance challenges remain. Machine-learning models require representative data reflecting climate-stressed conditions, and models trained primarily on historical stationary datasets may perform poorly under altered climate regimes. Integrating multi-model climate projections is therefore essential to avoid overconfidence and misestimation of risk (Liu et al., 2023). Algorithmic robustness and interpretability are also critical, as black-box models may fail under extreme outliers, necessitating explainable AI approaches and rigorous out-of-sample stress testing for safety-critical operations. Increased digitalization expands cybersecurity and privacy risks, making robust security architectures and privacy-preserving machine-learning methods prerequisites for deployment. Furthermore, market rules, regulatory frameworks, and institutional capacities must evolve to incentivize flexibility, resilience, and distributed AI-enabled services equitably, while the energy and material footprints associated with training large models and deploying edge intelligence require lifecycle assessment to prevent unintended emissions outcomes.

Given the deep uncertainty and non-stationarity introduced by climate change, a scenario-based, futures-oriented research approach is essential. Climate change affects not only mean conditions but also the variance and tails of weather and demand distributions, rendering single baseline forecasts increasingly obsolete. Scenario analysis that spans plausible climatic, socioeconomic, and technological pathways allows researchers and planners to identify strategies that remain robust across multiple futures rather than optimal under a single assumed trajectory. Because energy infrastructure investments entail long lifetimes, scenario-based approaches also help align long-term planning with flexible and adaptive architectures capable of performing under divergent climate outcomes (Kaplun, 2023; Liu et al., 2023). Integrating multi-model climate projections directly into AI system design and control development is therefore necessary to ensure algorithmic generalization under climate-altered conditions and to quantify residual risks (Liu et al., 2023). Scenario-based research additionally supports policy–technology co-design by informing regulatory pathways, market structures, and social acceptability considerations required to scale AI-enabled resilience services without exacerbating equity or governance challenges (Burgess et al., 2024).

This need is particularly acute in Iran, where distinctive climatic trends, energy mixes, and infrastructural constraints heighten vulnerability to climate-induced energy instability. Iran is experiencing rising temperatures, altered precipitation patterns, and increasing frequencies of extreme events, all of which affect hydropower reliability, thermal plant cooling, water availability, and temperature-driven electricity demand. The national energy system remains dominated by large centralized fossil-fuel generation while simultaneously possessing significant renewable potential and facing pronounced water–energy nexus pressures (Raymond et al., 2019; Takele et al., 2024). Key research priorities therefore include regionally downscaled climate-to-energy projections to capture localized changes in solar, wind, and hydrology for grid planning, building on global SDM approaches (Liu et al., 2023), as well as scenario-based evaluations of flexible energy architectures that combine storage, distributed renewables, demand response, and AI-based orchestration under socioeconomic pathways relevant to Iran's energy transition (Apribowo et al., 2022; Kaplun, 2023). Given water constraints and agricultural demands, AI-mediated co-optimization of energy and water systems, such as aligning desalination with renewable availability, is essential to avoid maladaptive investments (Dlamini et al., 2024; Zhang et al., 2025). Finally, research on governance, cybersecurity, and equitable market design, along with pilot deployments and living-lab experiments in Iranian microgrids and urban districts, is necessary to validate AI-enabled forecasting, robust optimization, and decentralized control under real climatic stressors while accounting for lifecycle and socio-economic impacts (Bulathwela et al., 2024; Burgess et al., 2024). This study addresses this gap by developing scenario-based futures for the integration of AI into climate-responsive energy systems. The following research questions are presented:

Q1. What are the key drivers affecting the future development of AI-enabled climate-responsive energy systems in Iran?

Q2. What are the plausible scenarios for the future of AI-enabled climate-responsive energy systems in Iran?

2. Literature Review

Chakraborty et al. (2021) proposed a scenario-based prediction approach using explainable artificial intelligence (XAI) to assess the impacts of climate change on building cooling energy consumption. Their XAI model predicted long-term cooling demand under different shared socioeconomic pathway (SSP) scenarios with high accuracy and identified critical outdoor temperature thresholds beyond which cooling energy consumption increases exponentially. The analysis, conducted for residential and commercial buildings across hot–humid and mixed–humid climates, revealed persistent growth in cooling energy demand from 2020 to 2100 under all SSPs, with more severe impacts under high-emission scenarios, highlighting the need for proactive adaptation and mitigation measures. Adapa (2024) examined the role of artificial intelligence in climate action, focusing on its applications in climate modeling, renewable energy optimization, and disaster response. Using a comprehensive literature review, case studies, and expert interviews, the study showed how AI improves climate prediction accuracy, supports climate scenario simulations, and enhances renewable energy forecasting, smart grid management, and energy storage optimization. The paper also highlighted AI-driven solutions for disaster preparedness, early warning systems, and post-disaster recovery, while discussing key challenges related to data quality, ethical concerns, and technical limitations, and emphasizing the importance of responsible AI deployment for effective climate mitigation and adaptation. Badekale et al. (2025) proposed an AI-driven approach for climate policy scenario generation in Sub-Saharan Africa using generative artificial intelligence. Their study employed large language models to simulate energy-transition-focused climate policy scenarios derived from historical United Nations Climate Change Conference (COP) documents, addressing limitations of traditional integrated assessment and expert-driven methods. Using an embedding-based evaluation framework and comparisons with human and machine evaluators, the results showed that most generated scenarios were coherent, plausible, and relevant, demonstrating the potential of generative AI as an effective tool for climate policy planning in data-constrained regions. Icaza Alvarez et al. (2025) conducted a bibliometric analysis of AI applications in the energy system transition, reviewing 342 Scopus-indexed publications from 1990 to 2024. Their study examined research evolution, key thematic areas, and collaboration patterns related to the integration of artificial intelligence and energy transition. The results showed rapid growth in AI-related energy research over the past five years, with AI playing an increasingly central role in renewable integration, energy market design, system optimization, and decarbonization efforts. The authors highlighted AI's expanding influence across energy supply chains and identified future research directions, including demand forecasting, dynamic energy distribution, and energy storage optimization. Pimenow et al. (2024) reviewed the challenges of artificial intelligence development in relation to energy consumption and climate change mitigation, emphasizing the dual role of AI as both an enabler of energy efficiency and a source of growing energy demand. Based on an analysis of 237 scientific publications from 2010 to 2024, the study identified rapid growth in AI and ML applications across sectors such as construction, transportation, industry, and households, particularly in energy optimization, renewable integration, and climate forecasting. The authors highlighted concerns regarding the high energy consumption of large-scale AI models and stressed the need for more energy-efficient AI architectures and advanced energy management strategies to maximize AI's contribution to sustainable development. Jain et al. (2023) investigated AI-enabled strategies for climate change adaptation aimed at protecting communities, infrastructure, and businesses from climate-related impacts. The study highlighted how artificial intelligence supports vulnerability assessment, climate scenario simulation, and risk analysis by processing large-scale data from climate models, satellite imagery, and other sources. While emphasizing AI's potential to enhance data-driven adaptation planning and resilience, the authors also addressed ethical concerns related to transparency, bias, and equity, underscoring the need for responsible and fair deployment of AI-based adaptation solutions. Ayadi et al. (2025) conducted a systematic literature review to examine how artificial intelligence contributes to enhancing system resilience to climate change across multiple sectors. Analyzing 385 peer-reviewed studies published between 2000 and early 2025 using the PRISMA protocol, the authors classified AI applications by sector, methodology, and relevance to adaptation and mitigation. The review revealed a dominant focus on adaptation-oriented applications, a prevalence of classical machine learning techniques, and significant regional and sectoral disparities, while highlighting persistent challenges related to data availability, model transparency, and equitable deployment, and emphasizing the need for region-specific and ethically grounded AI-driven resilience strategies. Ukoba et al. (2025) reviewed the application of artificial intelligence for predictive modeling of climate change impacts, with a focus on equitable governance and sustainable outcomes. Following the PRISMA framework, the study synthesized research on AI-based climate prediction, highlighting the role of machine learning and predictive analytics in modeling complex climate dynamics and future scenarios. The authors emphasized both the potential of AI to support policy-relevant decision-making and the challenges related to data gaps, model interpretability, and ethical use, underscoring the need for hybrid AI–physical models and improved data integration to enhance climate governance and resilience. Danish (2023) proposed a multidimensional framework to support the integration of artificial intelligence and machine learning into sustainable energy systems. Addressing the lack of comprehensive integration frameworks, the study employed a flexible multicriteria methodology to evaluate the feasibility of AI adoption and to rank energy systems based on their AI integration potential. The findings identified key AI and ML techniques capable of enhancing energy system performance and provided accessible, interdisciplinary insights to guide the development of AI-enabled pathways toward a sustainable energy future. Tasha (2025) reviewed applications of artificial intelligence in climate change mitigation, examining how AI techniques such as machine learning, deep learning, natural language processing, and remote sensing support emissions monitoring, weather forecasting, energy system optimization, and sustainable agriculture. The study also highlighted AI's role in disaster risk management through rapid data analysis and decision support. While emphasizing AI's potential to enhance climate mitigation efforts, the review identified key challenges related to energy consumption, data limitations, ethical concerns, and infrastructure constraints, particularly in resource-limited regions, and underscored the importance of energy-efficient AI models and responsible implementation. In addition to the energy–climate and AI-oriented literature, the methodological foundations of this study are aligned with established futures research practices that have been widely applied in Iranian and regional contexts using scenario development, structural analysis, and critical uncertainty logic. For instance, Fathi et al. (2022) developed future scenarios based on a critical uncertainty approach supported by multi-criteria techniques (DEMATEL/COPRAS), demonstrating how key uncertainties can be structured to generate plausible alternative futures. Similarly, Fathi et al. (2019) employed a cross-impact matrix combined with soft systems methodology to develop a futures-oriented understanding of complex socio-technical tourism systems, illustrating the value of mapping interdependencies and feedbacks among drivers before scenario formulation. At a broader regional level, Jandaghi et al. (2019) identified tourism scenarios in Turkey explicitly through a futures studies approach, reinforcing the applicability of scenario planning for policy-relevant exploration under uncertainty. Moreover, Torabi et al. (2023) used structural analysis to support futures studies and scenario development in food tourism, highlighting how influence–dependence logic helps identify dominant drivers and shape coherent scenario narratives. Collectively, these studies provide methodological support for adopting a structured futures studies framework in the present research, where cross-impact logic and MICMAC-based structural analysis are used to identify key drivers and critical uncertainties and to develop plausible scenarios for AI-enabled climate-responsive energy systems in Iran.

3. Research Methodology

This study is designed as an applied investigation and is grounded in a descriptive and analytical futures research framework, with particular attention to the evolution of Iran’s energy system. To effectively respond to the research objectives, a sequential mixed-methods strategy was adopted, integrating qualitative exploration with quantitative assessment in a complementary and staged manner. During the initial stage, semi-structured interviews were carried out with domain experts to uncover the principal forces influencing the future trajectory of AI-driven, climate-responsive energy systems in Iran. This stage focused on capturing a broad spectrum of determinants, including climatic conditions, technological advancement, economic dynamics, institutional structures, and governance mechanisms, all of which shape digital transformation and systemic resilience in the context of climate uncertainty. The qualitative material was examined using thematic and conceptual analysis, enabling the identification and synthesis of recurring patterns into a structured set of forward-looking drivers. In the subsequent stage, the extracted drivers were translated into a structured survey instrument aimed at assessing the interdependencies and directional influences among them. These data were analyzed through Cross-Impact Analysis using the MICMAC technique to map the influence–dependence relationships across variables. The results of this structural assessment were then used to isolate the most influential and uncertain drivers, which served as the foundation for developing alternative future scenarios for AI-enabled climate-adaptive energy systems in Iran. The expert group comprised 15 individuals with extensive experience in energy systems, climate science, artificial intelligence, and strategic foresight. Experts were recruited through purposive sampling, guided by criteria such as years of professional practice, participation in relevant national or international initiatives, and demonstrated familiarity with Iran’s energy governance and institutional environment. The panel included academic scholars, researchers in energy and climate fields, senior professionals from energy organizations, and specialists in digital transformation. In terms of demographics, the panel consisted of 60% male and 40% female participants. The mean age was 49 years, with participants ranging from 38 to 65 years old. Academically, two-thirds of the experts held doctoral degrees, while the remainder possessed master’s qualifications. Professional experience averaged 21 years, spanning a range from 12 to 30 years. With respect to specialization, 35% of the experts focused on energy policy and governance, 30% on energy systems and power networks, 20% on climate and environmental studies, and 15% on artificial intelligence and data analytics. The composition of the expert panel was deliberately structured to capture diverse yet complementary perspectives on the future of Iran’s energy system. In line with established conventions in expert-based futures research, sample adequacy was determined by the depth and diversity of insights and the attainment of analytical saturation rather than statistical representativeness. On this basis, the participation of 15 experts was deemed both sufficient and appropriate for fulfilling the aims of the study.

4. Analysis

This section begins by determining the principal factors expected to shape the future trajectory of AI-based climate-responsive energy systems in Iran. These factors were derived through an integrated process combining a systematic examination of the existing literature with detailed consultations involving field experts. The outcome of this stage was an initial pool of prospective drivers encompassing technological, climatic, economic, institutional, and governance-related aspects. To examine the significance and comparative weight of these drivers, a structured survey instrument was designed based on a five-point Likert scale. The survey items were formulated to elicit expert judgments on how artificial intelligence contributes to enhancing the adaptability and resilience of energy systems in the context of climate change. The questionnaire was administered to a purposively selected group of experts, all of whom returned complete responses. The collected data were subsequently processed using SPSS software, and drivers meeting the statistical significance criterion of 0.05 were retained as key determinants based on expert agreement. A summary of the validated drivers and the corresponding statistical results is presented in Table 1.

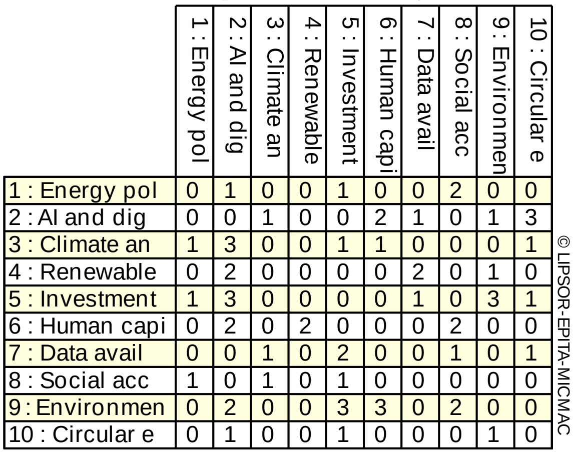
Table 1. Key drivers influencing the future of AI-enabled Climate-Responsive energy systems in Iran.

No	Key driver	Description	Source	Sig
1	Energy policy and governance reform	Credible, long-term renewable and AI policies, subsidy reform, and adaptive governance are essential for transition in fossil-rich Iran, where weak policy credibility and lack of sustainability recognition have constrained renewable deployment and energy transition efforts.	(Aghlimoghadam, 2025; Heidary et al., 2025; Danish & Senjyu, 2023)	.010
2	AI and digital infrastructure capacity	Availability of data platforms, communication networks, and computing resources determines whether AI can model demand, integrate renewables, and manage complex grids in practice, especially in developing countries with infrastructure gaps.	(Talha et al., 2025; Banaeian et al., 2020; Alvarez et al., 2025; Chen et al., 2025), Interview with experts	.025
3	Climate and energy security pressures	Rising climate risks and chronic energy supply–demand imbalances in Iran (e.g., electricity security challenges) act as a trigger for diversification toward low-carbon, climate-adaptive energy pathways and strengthen the case for AI-based planning tools.	(Razaghi et al., 2025; Heidary et al., 2025; Aghlimoghadam, 2025)	.015
4	Renewable resource potential and hybrid system deployment	High solar and wind potential and proven techno-economic performance of hybrid renewable systems in Iran create a strong technical basis for AI optimization of generation, storage, and dispatch to reduce CO_2 emissions and costs.	(Razmjoo et al., 2021; Nabavi et al., 2020; Razaghi et al., 2025)	.018
5	Investment, climate finance, and R&D funding	Domestic and international climate finance, plus targeted R&D funding for AI in renewables, significantly strengthens AI’s positive impact on renewable energy development and accelerates clean-energy innovation.	(Zhao et al., 2024; Yin et al., 2023; Olawade et al., 2024)	.023
6	Human capital and interdisciplinary expertise	Shortages of AI, data-science, and energy-systems skills in developing contexts limit deployment; future progress depends on capacity building, digital literacy, and cross-disciplinary collaboration between environmental and AI experts.	(Talha et al., 2025; Banaeian et al., 2020; Arévalo-Royo et al., 2025; Olawade et al., 2024), Interview with experts	.033
7	Data availability, quality, and interoperability	Localized, high-resolution, and integrated datasets (climate, grid, demand, water–food–energy) are critical for reliable AI models; current gaps in data access and integration are a major barrier in Iran and the wider region.	(Talha et al., 2025; Razaghi et al., 2025; Alvarez et al., 2025; Banaeian et al., 2020)	.011
8	Social acceptance, equity, and inclusion	Public trust, fairness, and attention to social factors (e.g., rural communities, agriculture, energy poverty) shape adoption of AI-enabled energy systems and are increasingly recognized as necessary for sustainable transitions in Iran.	(Banaeian et al., 2020; Arévalo-Royo et al., 2025; Danish & Senjyu, 2023; Alvarez et al., 2025)	.002
9	Environmental and market-based policy stringency	Strong, especially market-based, environmental policies (carbon pricing, green R&D support) amplify AI’s positive effect on shifting energy systems toward renewables and high-quality energy development.	(Yin et al., 2023; Wang, 2025; Zhao et al., 2024), Interview with experts	.037
10	Circular economy and resource-efficiency orientation	Aligning AI-driven energy policies with circular economy principles (recycling, efficiency, life-cycle thinking) supports lower emissions, better resource use, and more sustainable energy system design.	(Danish & Senjyu, 2023; Olawade et al., 2024)	.020

Once the core drivers listed in Table 1 were finalized, they were subjected to a deeper examination to reveal the patterns of interaction among them and to clarify their relative importance within a formal influence–dependence structure To achieve this, a uniform evaluation tool was developed and distributed to the expert panel, requesting assessments of both the direct influence exerted by each driver and its susceptibility to influence from others. The expert evaluations were then consolidated, and mean values were calculated for each variable and reported in Table 2. These aggregated scores were subsequently processed using the MICMAC technique, which allowed the drivers to be systematically grouped into influential, linking, dependent, and autonomous categories. This structured classification formed the analytical basis for constructing alternative and plausible future scenarios for AI-enabled climate-responsive energy systems in Iran.

Once the survey data were processed within the MICMAC analytical environment, the network of direct and indirect relationships among the key drivers influencing the future trajectory of AI-enabled climate-responsive energy systems in Iran was systematically analyzed. This analysis allowed for a quantitative assessment of the extent to which each driver exerts influence on, and responds to, other drivers in the system. The resulting matrices of direct and indirect effects are presented in Tables 3 and 4, where the intensity of interactions is mapped across corresponding rows and columns. It is important to emphasize that the numerical outputs of these matrices are produced through the internal computational logic of the MICMAC software and are intended to facilitate relative and comparative analysis of driver interdependencies rather than to serve as absolute quantitative indicators.

Table 2. Cross-Impact matrix of key drivers.



	1 : Energy pol	2 : AI and dig	3 : Climate an	4 : Renewable	5 : Investment	6 : Human capi	7 : Data avail	8 : Social acc	9 : Environmen	10 : Circular e
1 : Energy pol	0	1	0	0	1	0	0	2	0	0
2 : AI and dig	0	0	1	0	0	2	1	0	1	3
3 : Climate an	1	3	0	0	1	1	0	0	0	1
4 : Renewable	0	2	0	0	0	0	2	0	1	0
5 : Investment	1	3	0	0	0	0	1	0	3	1
6 : Human capi	0	2	0	2	0	0	0	2	0	0
7 : Data avail	0	0	1	0	2	0	0	1	0	1
8 : Social acc	1	0	1	0	1	0	0	0	0	0
9 : Environmen	0	2	0	0	3	3	0	2	0	0
10 : Circular e	0	1	0	0	1	0	0	0	1	0

Table 3. Direct influence matrix of key drivers shaping the future of AI-enabled Climate-Responsive energy systems in Iran.

N°	Variable	Total number of rows	Total number of columns
1	Energy policy and governance reform	4	3
2	AI and digital infrastructure capacity	8	14
3	Climate and energy security pressures	7	3
4	Renewable resource potential and hybrid system deployment	5	2
5	Investment, climate finance, and R&D funding	9	9
6	Human capital and interdisciplinary expertise	6	6
7	Data availability, quality, and interoperability	5	4
8	Social acceptance, equity, and inclusion	3	7
9	Environmental and market based policy stringency	10	6
10	Circular economy and resource efficiency orientation	3	6
	Totals	60	60

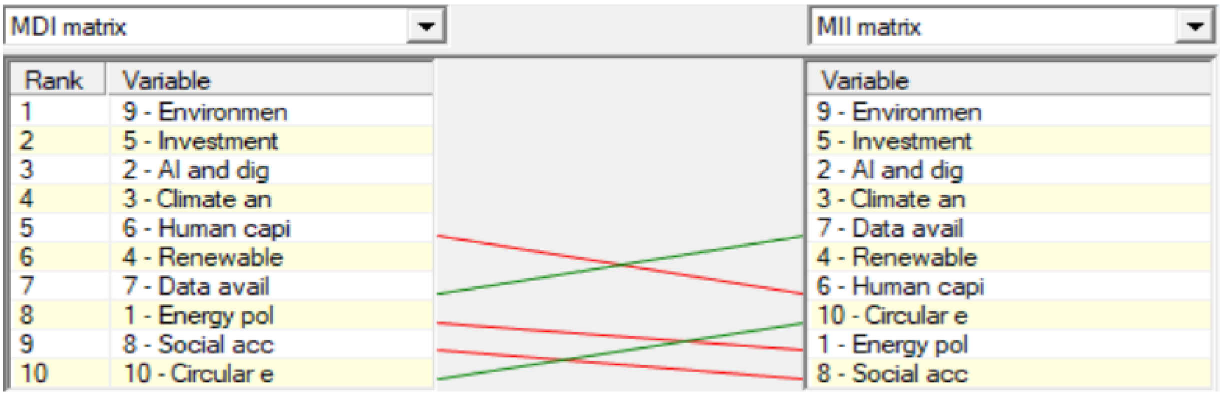
Table 4. Indirect influence matrix of key drivers shaping the future of AI-enabled Climate-Responsive energy systems in Iran.

N°	Variable	Total number of rows	Total number of columns
1	Energy policy and governance reform	149	104
2	AI and digital infrastructure capacity	289	507
3	Climate and energy security pressures	277	134
4	Renewable resource potential and hybrid system deployment	215	98
5	Investment, climate finance, and R&D funding	411	337
6	Human capital and interdisciplinary expertise	198	318
7	Data availability, quality, and interoperability	225	142
8	Social acceptance, equity, and inclusion	135	261
9	Environmental and market based policy stringency	420	278
10	Circular economy and resource efficiency orientation	176	316
	Totals	60	60

Using the MICMAC tool, the identified drivers were analyzed and ordered according to the intensity of their direct and indirect interactions within the system. This analytical procedure made it possible to differentiate variables that exert a strong structuring influence from those whose behavior is largely shaped by other drivers. The results of this influence–dependence mapping are depicted in Figs. 1 and 2, which shed light on the fundamental structural mechanisms shaping the future trajectory of AI-enabled climate-responsive energy systems in Iran.

As shown in Fig. 1, the direct influence analysis indicates that Environmental and market-based policy stringency (Driver 9) and Investment, climate finance, and R&D funding (Driver 5) ranked first and second, respectively. This result underscores their dominant role in shaping the future development of AI-enabled climate-responsive energy systems in Iran, highlighting the critical importance of policy rigor and financial capacity in steering technological adoption and system transformation.

As illustrated in Fig. 2, AI and digital infrastructure capacity (Driver 2) and investment, climate finance, and R&D funding (Driver 5) occupy the first and second positions, respectively, in terms of indirect dependence within the system. Furthermore, Table 5 presents a structured ranking of the identified key drivers influencing the future of AI-enabled climate-responsive energy systems in Iran, based on their relative levels of direct influence, indirect effects, and dependency relationships.



Rank	Variable	Variable
1	9 - Environmen	9 - Environmen
2	5 - Investment	5 - Investment
3	2 - AI and dig	2 - AI and dig
4	3 - Climate an	3 - Climate an
5	6 - Human capi	7 - Data avail
6	4 - Renewable	4 - Renewable
7	7 - Data avail	6 - Human capi
8	1 - Energy pol	10 - Circular e
9	8 - Social acc	1 - Energy pol
10	10 - Circular e	8 - Social acc

Fig. 1. Classification of drivers based on their direct and indirect impact levels.

Rank	Variable	Variable
1	2 - AI and dig	2 - AI and dig
2	5 - Investment	5 - Investment
3	8 - Social acc	6 - Human capi
4	6 - Human capi	10 - Circular e
5	9 - Environmen	9 - Environmen
6	10 - Circular e	8 - Social acc
7	7 - Data avail	7 - Data avail
8	1 - Energy pol	3 - Climate an
9	3 - Climate an	1 - Energy pol
10	4 - Renewable	4 - Renewable

Fig. 2. Classification of drivers based on their direct and indirect dependency levels

Table 5. Direct and indirect impact and dependency scores of key drivers

Rank	Label	Direct influence	Label	Direct dependence	Label	Indirect influence	Label	Indirect dependence
1	Environmen	1666	AI and dig	2333	Environmen	1683	AI and dig	2032
2	Investment	1500	Investment	1500	Investment	1647	Investment	1350
3	AI and dig	1333	Social acc	1166	AI and dig	1158	Human capi	1274
4	Climate an	1166	Human capi	1000	Climate an	1110	Circular e	1266
5	Human capi	1000	Environmen	1000	Data avail	901	Environmen	1114
6	Renewable	833	Circular e	1000	Renewable	861	Social acc	1046
7	Data avail	833	Data avail	666	Human capi	793	Data avail	569
8	Energy pol	666	Energy pol	500	Circular e	705	Climate an	537
9	Social acc	500	Climate an	500	Energy pol	597	Energy pol	416
10	Circular e	500	Renewable	333	Social acc	541	Renewable	392

As presented in Fig. 3, climate and energy security pressures (Driver 3) together with environmental and market-based policy stringency (Driver 9) are identified as the dominant forces influencing the future trajectory of AI-enabled climate-responsive energy systems in Iran. Within the analytical structure, these drivers function as input variables that lie largely beyond the direct operational control of the energy system. Owing to their exogenous nature and relative stability over time, they constitute essential boundary conditions for scenario development and provide a robust basis for long-term strategic analysis.

After determining the positional roles of the key drivers shaping the future of AI-enabled climate-responsive energy systems in Iran, their mutual relationships and interaction patterns were systematically examined using the MICMAC software. The analysis produced detailed representations of both direct and indirect effects among the drivers, which are presented in Figs. 4 and 5. These visualizations offer an integrated view of the system's structural configuration and highlight the underlying influence–dependence dynamics governing its evolution.

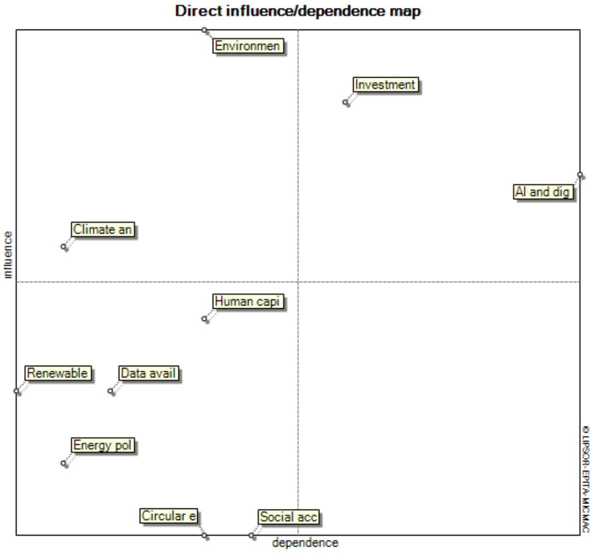


Fig. 3. Diagram of key drivers' status in the output of Mic Mac software.

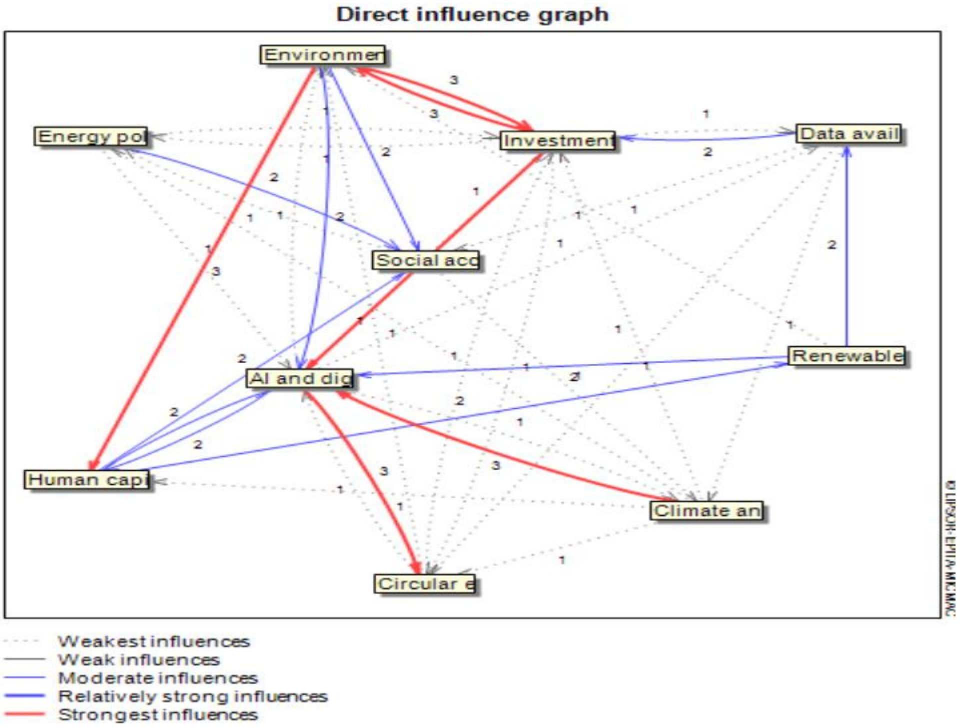


Fig. 4. Direct impacts of drivers (from very weak to very strong impacts).

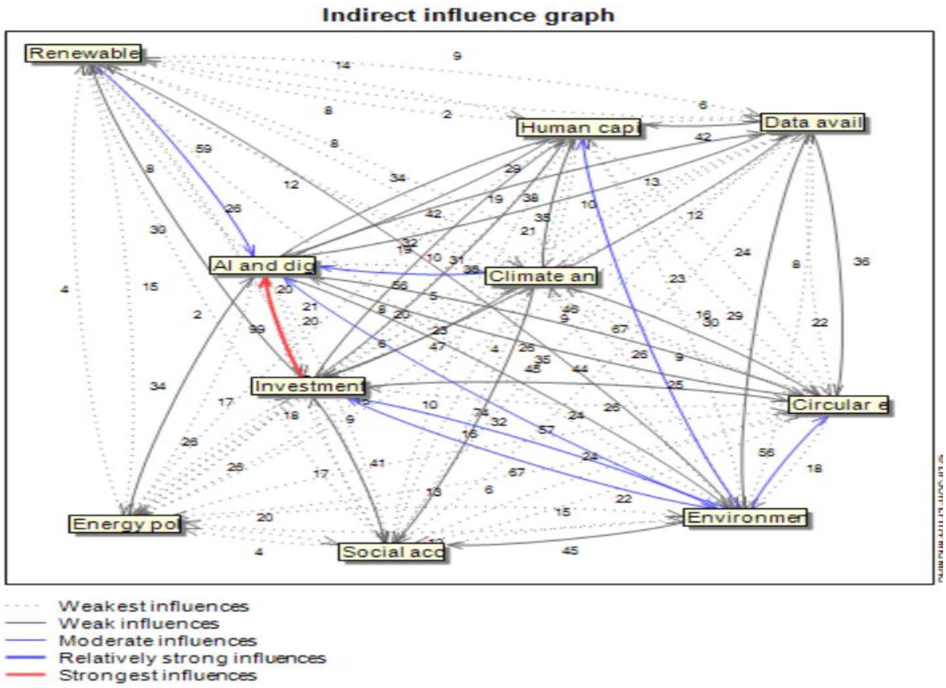


Fig. 5. Indirect impacts of drivers (from very weak to very strong impacts).

Building on the results of the MICMAC analysis, climate and energy security pressures (Driver 3) and environmental and market-based policy stringency (Driver 9) were selected as the critical uncertainties underpinning scenario development. By examining the alternative states of these two drivers, four distinct and plausible future scenarios for the evolution of AI-enabled climate-responsive energy systems in Iran were constructed. The driver climate and energy security pressures was conceptualized along a continuum ranging from moderate and manageable pressures to severe and escalating climate–energy security stresses. In parallel, environmental and market-based policy stringency was defined through two contrasting conditions: weak and fragmented regulatory enforcement versus strong, coordinated, and market-oriented environmental regulation. The intersection of these driver states generated a 2×2 scenario matrix, resulting in four scenarios that reflect divergent pathways for system adaptation, governance, and technological deployment. Fig. 6 presents these scenarios and their corresponding titles, each capturing the dominant dynamics and strategic conditions shaping the future trajectory of Iran’s climate-responsive energy systems.

Scenario 1: The Wisdom of Anahita

Named after Anahita, a figure in Persian mythology symbolizing wisdom, order, and the sustainable stewardship of vital resources particularly water this scenario represents a future pathway grounded in anticipatory governance, balance, and rational management rather than reactive crisis response. The designation reflects a development trajectory in which foresight, regulatory coherence, and informed decision-making guide the integration of artificial intelligence into the energy system, ensuring stability and gradual adaptation in the face of emerging climate risks. In this scenario, climate and energy security pressures remain at a relatively moderate and manageable level and do not escalate into a systemic or nationwide crisis. Nevertheless, policymakers and institutions recognize the long-term risks associated with climate change and energy vulnerability and proactively pursue structural and regulatory reforms. Environmental and market-based policies are designed and implemented in a coordinated and consistent manner, providing clear and credible signals to market participants. Stable, transparent, and predictable regulatory frameworks reduce uncertainty and create an enabling environment for the gradual yet systematic deployment of AI-enabled solutions across the energy system. Within this context, artificial intelligence is not mobilized as an emergency response tool, but rather as a strategic enabler of efficiency, foresight, and resilience. AI-driven forecasting models, integrating climate data with real-time grid and demand information, allow system operators and decision-makers to anticipate fluctuations in supply and demand with greater accuracy.

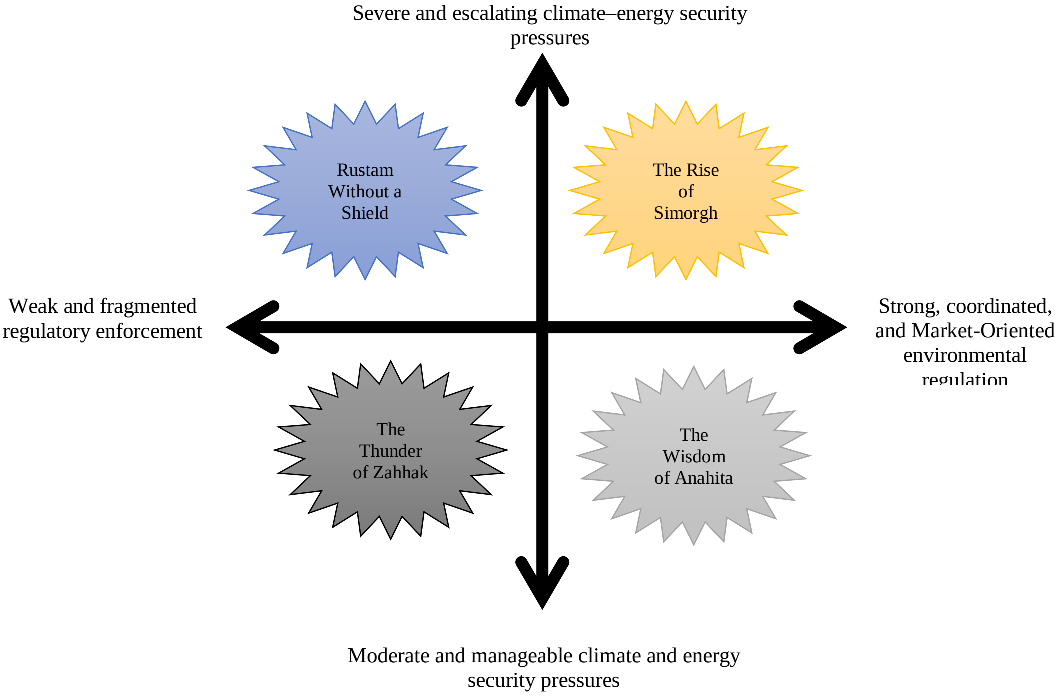


Fig. 6. Plausible future scenarios for AI-enabled climate-responsive energy systems in Iran.

These insights support optimized dispatch, demand-side management, and the intelligent use of energy storage, thereby mitigating costly imbalances before they materialize. In parallel, digitalization of the grid progresses incrementally, accompanied by improvements in data standardization, interoperability, and cybersecurity, ensuring that information infrastructures remain reliable and trustworthy. From an investment perspective, regulatory stability and policy clarity lower perceived risks and encourage sustained, targeted capital flows into renewable energy, hybrid systems, storage technologies, and digital infrastructure. Although investment growth is not rapid or disruptive, it is continuous and strategically aligned with long-term transition objectives. Gradual reforms in electricity market design, combined with economic incentives for flexibility and efficiency, foster private sector participation and support innovation in AI-based energy applications. Over time, this pathway leads to steady improvements in system performance, reduced long-term operational costs, and enhanced adaptive capacity to future climate-related shocks. The principal vulnerability of this scenario lies in the very conditions that enable its stability. Because climate and energy pressures remain relatively contained, there is a risk of complacency and delayed action. The pace of technological and institutional transformation may fall short of what would be required under more extreme future conditions. Should climate impacts intensify beyond current expectations, an energy system shaped primarily by incremental optimization may face the need for abrupt acceleration in investment and decision-making. Nonetheless, the emphasis on foresight, governance quality, and strategic use of AI provides a strong foundation for adaptation, making this scenario a benchmark of prudent and balanced transition rather than a fragile equilibrium.

Scenario 2: The Thunder of Zahhak

Named after Zahhak, a figure in Persian mythology symbolizing short-sighted power, neglect of wisdom, and the gradual emergence of latent destruction beneath apparent stability, this scenario reflects a future in which underlying risks are underestimated and governance fails to keep pace with emerging challenges. The name captures a pathway where warning signs exist but are not translated into coherent action, allowing vulnerabilities to accumulate beneath a seemingly manageable surface. In this scenario, climate and energy security pressures remain at a moderate and relatively controllable level and do not yet escalate into acute systemic crises. Energy supply disruptions, climate-related extremes, and geopolitical stresses occur intermittently but are generally absorbed by existing infrastructure and operational practices. However, despite this window of relative stability, environmental and market-based policy stringency remains weak, fragmented, and inconsistently enforced.

Regulatory frameworks lack coherence, long-term vision, and credible enforcement mechanisms, resulting in ambiguous signals for market actors and system operators. Within this governance context, the deployment of artificial intelligence in the energy sector proceeds in an ad hoc and uneven manner. AI applications emerge primarily through isolated pilot projects, localized operational tools, or short-term efficiency initiatives rather than as components of an integrated national strategy. Forecasting models, digital monitoring systems, and optimization tools are adopted selectively by individual utilities or regions, but their impact remains limited due to poor data interoperability, absence of shared standards, and weak institutional coordination. As a result, AI contributes to incremental operational improvements without fundamentally enhancing system-level resilience or adaptability. Investment patterns in this scenario are cautious and fragmented. The absence of strong regulatory commitment and market-based incentives discourages large-scale or long-horizon investment in renewable energy, storage, and digital infrastructure. Capital flows tend to favor low-risk, short-payback projects rather than transformative system upgrades. Private sector participation remains constrained, while public investment is often reactive and driven by immediate operational needs rather than strategic climate adaptation objectives. Consequently, the integration of hybrid energy systems and advanced AI-enabled control architectures progresses slowly and unevenly. Over time, the structural weaknesses of this pathway become increasingly apparent. Although the system does not immediately collapse under climate stress, its capacity to absorb shocks erodes gradually. The lack of coordinated policy action and institutional learning means that each disruption whether climatic, economic, or technical is addressed in isolation, preventing cumulative improvements in resilience. Social trust in energy governance may weaken as inefficiencies, regional disparities, and repeated minor disruptions persist without clear corrective direction. The defining risk of this scenario lies in missed opportunity. By failing to leverage a period of manageable climate and energy pressures to implement robust governance reforms and scalable AI integration, the system becomes progressively more vulnerable to future shocks. When pressures eventually intensify beyond moderate levels, the accumulated deficits in infrastructure, policy coherence, and digital capacity may force abrupt and costly adjustments. In this sense, The Thunder of Zahhak represents a deceptive calm one in which the absence of immediate crisis masks the slow buildup of systemic fragility.

Scenario 3: Rustam Without a Shield

Drawing on the Persian epic hero Rustam renowned for strength and courage, yet rendered vulnerable when deprived of protection this scenario symbolizes a future in which the energy system is exposed to severe external threats without the institutional and policy safeguards necessary for effective defense. The name reflects a condition of structural exposure: the system confronts escalating climate and energy security pressures with determination and effort, but lacks the regulatory coherence and strategic governance required to withstand them sustainably. In this scenario, climate change impacts and energy security challenges intensify markedly. Rising temperatures, prolonged heatwaves, water scarcity, and increasing frequency of extreme events place sustained stress on energy supply, transmission infrastructure, and demand patterns. At the same time, geopolitical uncertainties and resource constraints heighten risks to fuel availability and system reliability. These pressures are no longer episodic but persistent, pushing the energy system into a near-continuous state of strain. Despite the severity of these conditions, environmental and market-based policy stringency remains weak, fragmented, and inconsistently enforced, preventing the emergence of a coordinated national response. Within this context, the deployment of artificial intelligence is largely reactive and crisis-driven. AI tools are introduced primarily to manage immediate disruptions, such as forecasting short-term demand spikes, detecting grid anomalies during extreme weather, or optimizing emergency dispatch under constrained conditions. While these applications provide temporary relief, they are not embedded within a comprehensive governance or market framework that would allow AI to contribute to long-term system transformation. Data infrastructures remain incomplete and poorly standardized, limiting model reliability and reducing the effectiveness of advanced analytics under rapidly changing conditions. Investment behavior in this scenario is dominated by urgency rather than strategy. Public resources are diverted toward short-term stabilization measures, maintenance backlogs, and emergency repairs, leaving little fiscal space for long-term adaptation or digital modernization. Private investment is discouraged by regulatory uncertainty, price distortions, and the absence of credible market signals, resulting in underinvestment in renewable energy, storage technologies, and AI-enabled control systems. As a consequence, hybrid energy systems and decentralized solutions develop slowly and unevenly, failing to keep pace with the growing scale of climate-induced stress. Over time, the cumulative effects of high pressure and weak governance erode system resilience. Each climatic shock or supply disruption is addressed in isolation, without institutional learning or structural improvement, reinforcing a cycle of vulnerability. Operational fatigue, infrastructure degradation, and widening regional disparities become more pronounced, while public confidence in energy governance deteriorates. The energy system remains functional but brittle capable of enduring stress in the short term, yet increasingly prone to cascading failures under compound or extreme events. The central risk embodied in Rustam Without a Shield is exhaustion without adaptation. Strength and effort alone are insufficient when not reinforced by protective institutions, coherent policy frameworks, and forward-looking regulation. In the absence of decisive governance reform, escalating climate and energy security pressures transform from external challenges into internal sources of systemic fragility. This scenario thus represents a pathway in which resilience is continually tested but never fully built, leaving the energy system exposed at precisely the moment when robust protection is most urgently needed.

Scenario 4: The Rise of Simorgh

Named after the Simorgh, the mythical Persian bird symbolizing rebirth, collective wisdom, and emergence through adversity, this scenario represents a future in which severe climate and energy security pressures act as a catalyst for deep institutional reform and strategic transformation. Rather than overwhelming the system, escalating risks trigger a coordinated and purposeful response, enabling artificial intelligence to become a central instrument for resilience, adaptation, and long-term sustainability. In this scenario, climate change and energy security challenges intensify substantially, placing persistent and systemic stress on energy supply, infrastructure, and demand. Extreme heat events, water scarcity, and variability in renewable generation coincide with heightened risks to fuel availability and grid reliability. However, unlike in pathways characterized by fragmented governance, these pressures are met with strong, coherent, and market-oriented environmental policies. Regulatory frameworks are tightened, enforcement mechanisms are strengthened, and economic instruments such as carbon pricing, flexibility markets, and performance-based incentives are deployed to align public and private decision-making with resilience and decarbonization objectives. Within this policy environment, artificial intelligence evolves from a supportive technology into a core component of system governance and operation. AI-driven probabilistic forecasting integrates climate projections with real-time operational data to anticipate stress conditions and guide preemptive interventions. Robust optimization and adaptive control algorithms are embedded across generation, transmission, and distribution layers, enabling the system to function reliably under deep uncertainty. Decentralized intelligence and edge-based control architectures support microgrids, islanding strategies, and self-healing capabilities, reducing the risk of cascading failures during extreme events. Investment dynamics in this scenario are reshaped by credible and consistent policy signals. High climate pressure, combined with regulatory clarity, mobilizes substantial public and private capital toward renewable energy, hybrid systems, energy storage, and digital infrastructure. Long-term financing mechanisms and climate-oriented investment frameworks reduce risk premiums and encourage innovation at scale. As a result, AI-enabled energy solutions are deployed systemically rather than selectively, accelerating the transition toward flexible, low-carbon, and climate-adaptive energy architectures. Over time, the interaction between strong governance and advanced digital capabilities transforms crisis into opportunity. Institutional learning improves, data ecosystems mature, and standards for interoperability, cybersecurity, and transparency are reinforced. Social acceptance of reform increases as the benefits of enhanced reliability, reduced disruption, and more equitable energy access become visible. Although the system operates under continuous climatic stress, its capacity to anticipate, absorb, and recover from shocks is significantly enhanced. The defining characteristic of The Rise of Simorgh is transformation through pressure. Severe climate and energy security challenges do not merely test the system; they reshape it. By aligning stringent policy frameworks with the strategic deployment of artificial intelligence, this scenario illustrates a pathway in which resilience is actively constructed, rather than passively endured. It represents the most adaptive and forward-looking future among the four scenarios, demonstrating how adversity, when met with collective wisdom and decisive governance, can give rise to a stronger and more sustainable energy system.

A comparative synthesis of the four scenarios is provided in Table 6, highlighting differences in governance conditions, the expected role of AI, investment trajectories, and resilience outcomes under varying climate–energy security pressures.

5. Discussion and Conclusion

The findings of this study demonstrate that the future trajectory of AI-enabled climate-responsive energy systems in Iran is not determined solely by technological progress, but is fundamentally shaped by the interaction between climate–energy security pressures and the quality of environmental and market-based governance. The cross-impact analysis conducted using the MICMAC method revealed that climate and energy security pressures and environmental and market-based policy stringency function as exogenous, input drivers within the system and exert the strongest influence over other variables. This result indicates that the pathway of digital transformation and the effective deployment of artificial intelligence in the energy sector are influenced more by macro-level climatic conditions and institutional–policy frameworks than by isolated, sector-specific technological choices. The scenario outcomes further suggest that under conditions of manageable climate and energy pressures, the presence of strong, coherent, and coordinated policy frameworks enables a gradual yet sustainable pathway for AI integration. In such a context, artificial intelligence is primarily deployed as a tool for optimization, forecasting, and incremental enhancement of system resilience, rather than as an emergency response mechanism. Conversely, weak and fragmented policy regimes under similar low-pressure conditions lead to missed opportunities, fragmented digital initiatives, and the gradual accumulation of systemic vulnerabilities. Although this pathway may not appear critical in the short term, it undermines the foundations of long-term resilience and adaptive capacity. As climate and energy security pressures intensify, the role of governance becomes increasingly decisive.

Table 6. Comparison of the four scenarios of AI-enabled climate-responsive energy systems in Iran.

Scenario	Climate & energy security pressures	Environmental & market-based policy stringency	Role of AI in the system	Investment & infrastructure trajectory	System-level outcomes	Main risks / failure modes
Anahita	Moderate / manageable	Strong, coherent, market-oriented	Strategic enabler (forecasting, optimization, gradual resilience-building)	Steady, aligned investment in renewables, storage, data platforms; incremental grid digitalization	Gradual improvement in reliability, efficiency, and adaptive capacity	Complacency; pace may be too slow if climate risks accelerate
Zahhak	Moderate / manageable	Weak, fragmented, inconsistent enforcement	Ad hoc / local pilots; limited interoperability and scaling	Cautious, short-horizon investment; fragmented digital upgrades	Incremental gains but weak system resilience; vulnerabilities accumulate	“Missed opportunity” during stable window; future shocks force abrupt costly adjustment
Rustam	High / escalating	Weak, fragmented, inconsistent enforcement	Reactive crisis tool (short-term forecasting, anomaly detection, emergency dispatch)	Emergency spending dominates; underinvestment in long-term renewables/storage/data ecosystems	System remains functional but brittle; higher likelihood of cascading failures	Exhaustion without adaptation; widening regional inequality; declining public trust
Simorgh	High / escalating	Strong, coherent, market-oriented	Core operating logic (probabilistic forecasting, robust optimization, decentralized control, self-healing)	Large-scale mobilization of public/private finance; accelerated digital & renewable build-out	Structural transformation; higher resilience under deep uncertainty	Implementation complexity; governance/cybersecurity and equity must keep pace

The scenario analysis shows that in the absence of coherent and enforceable policy frameworks, even substantial technical efforts and limited AI deployment are insufficient to prevent progressive system degradation and growing fragility in the face of compound shocks. By contrast, when high levels of climate pressure coincide with stringent, coordinated, and market-oriented environmental policies, these pressures can be transformed into drivers of structural change. Under such conditions, artificial intelligence can be systematically embedded in forecasting, decentralized control, robust optimization, and crisis management, enabling the energy system to operate effectively under deep uncertainty. This finding underscores that climate stress does not inevitably lead to system failure; rather, under effective governance, it can act as a catalyst for accelerated transition and resilience-building. Based on these results, several strategic implications emerge for energy policymakers and planners in Iran. First, the development of AI applications in the energy sector without parallel institutional and policy reforms is likely to yield limited benefits and may even exacerbate regional inequalities and systemic inefficiencies. Second, investments in digital infrastructure, data ecosystems, and artificial intelligence must be embedded within transparent, stable, and market-based policy frameworks in order to build investor confidence and attract long-term private capital. Third, future climate pressures are unavoidable, and delays in strengthening environmental governance and regulatory mechanisms will increase the costs of adaptation in a non-linear manner over time. In conclusion, this study suggests that a desirable future for AI-enabled climate-responsive energy systems in Iran does not lie in eliminating uncertainty, but in managing it intelligently. The scenario-based approach adopted in this research enables policymakers to move beyond linear and overly optimistic planning assumptions and instead consider a range of plausible futures. This perspective supports the design of flexible, robust, and learning-oriented strategies capable of adapting to evolving climatic and institutional conditions. Future research is recommended to build on this framework by quantifying the impacts of each scenario, examining energy justice implications, and analyzing the role of data governance and cybersecurity in enabling responsible and resilient AI deployment in the energy sector.

This study has several limitations. First, the scenario construction relies on a purposive expert panel (n=15); while appropriate for foresight research, the resulting influence–dependence judgments may reflect panel composition and subjective bias rather than statistical representativeness. Second, MICMAC-based structural analysis translates qualitative assessments into a cross-impact matrix; despite its usefulness for mapping systemic interdependencies, outcomes can be sensitive to how variables are defined, the scoring scale used, and the aggregation procedure. Third, the scenario space is generated from two critical uncertainties (climate–energy security pressures and environmental/market-based policy stringency). This improves clarity, but may under-represent other deep uncertainties (e.g., geopolitical shocks, sanctions, cyber risks, or breakthrough innovations) that could significantly reshape AI adoption pathways.

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