KMAN PUBLISHING INSTITUTE

Article history:
Received 20 August 2026
Revised 29 October 2026
Accepted 05 November 2026
Initial Publish 27 November 2026
Published online 01 January 2028

Journal of Resource Management and Decision Engineering

Volume 7, Issue 1, pp 1-24



Development of an Agent-Based Sustainability Model for Iran's Power Generation Industry

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A r t i c l e I n f o

Article type:
Original Research

How to cite this article:
Fallah Faal, S., Mohtashami, A., & Ehtesham Rasi, R. (2028). Development of an Agent-Based Sustainability Model for Iran's Power Generation Industry. *Journal of Resource Management and Decision Engineering*, *7*(1), 1-24.
https://doi.org/10.61838/kman.jrmde.477

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A B S T R A C T

This study develops a comprehensive and dynamic agent-based model for assessing sustainability in Iran's power-generation industry, with Shahid Montazer Ghaem Power Plant as the empirical context. The research is applied in purpose and follows an exploratory mixed-method design. First, thematic analysis was used to convert expert knowledge into a structured sustainability framework. The detailed qualitative phase involved a purposively selected panel of 25 power-sector experts representing electrical and mechanical engineering, industrial engineering, energy and environmental management, policy, and academic research. Thematic coding produced 487 meaningful statements, 112 initial codes, 36 basic themes, 12 organizing themes, and six global themes. Second, the qualitative findings were operationalized in Net-Logo as an agent-based model with three principal agent types: power plants, a regulator, and electricity demanders. The model represents production capacity, efficiency, failures, fuel and water consumption, emissions, costs, revenues, profit, regulatory instruments, and demand growth. Eight policy and stress scenarios were examined. The results show that power-plant sustainability emerges from nonlinear interactions among technical, economic, environmental, resource, institutional, and human dimensions. Technical performance especially equipment reliability, efficiency, and preventive maintenance acts as a critical bottleneck, while water and fuel constraints sharply reduce supply adequacy. Technology upgrading and an integrated policy package produced the strongest overall sustainability outcomes. The proposed model provides a decision-support framework for testing policies before implementation and for identifying leverage points for sustainable power-plant management.

Keywords: *Sustainability; Agent-Based Modeling; Power Plants; Thematic Analysis; Net-Logo; Decision Support.*

1. Introduction

The transition toward sustainable energy systems has become one of the defining technological, economic, and environmental challenges of contemporary development. Electricity systems are expected not only to satisfy rapidly growing demand but also to reduce greenhouse-gas emissions, improve resource efficiency, maintain operational reliability, and remain economically viable under changing technological and regulatory conditions. These requirements have substantially expanded the meaning of sustainability in the power sector. Sustainable electricity generation can no longer be evaluated solely in terms of installed capacity or generation cost; instead, it requires simultaneous consideration of technical performance, environmental impacts, economic continuity, resource security, infrastructure resilience, and policy effectiveness. At the global level, the transformation of power infrastructure increasingly depends on the interaction between conventional generating assets, renewable technologies, storage systems, advanced materials, digital management, and environmental regulation, making sustainability an inherently systemic rather than isolated engineering problem (Farfan Orozco, 2020; Yutong, 2025).

This systemic perspective has become particularly important as countries attempt to reconcile energy security with decarbonization. The experience of major energy transitions demonstrates that replacing or modifying established generation structures requires more than simply increasing renewable capacity. Sustainable transformation depends on the compatibility of generation technologies, transmission infrastructure, storage capacity, market arrangements, regulatory mechanisms, and patterns of electricity consumption. The German energy transition, for example, illustrates the importance of considering the power system as an integrated technological and institutional structure in which generation, networks, flexibility, and long-term system stability must develop simultaneously (Beck, 2025). Likewise, research on the diversification of energy supply indicates that technological and resource diversification can strengthen resilience by reducing excessive dependence on a limited number of fuels or generation technologies and by enabling energy systems to respond more effectively to uncertainty and transition-related disruptions (Gitelman et al., 2023). Consequently, sustainability in electricity generation should be regarded as an emergent property of interacting subsystems rather than the result of optimizing a single performance indicator.

Technological innovation is central to this transformation. Improvements in materials engineering, generation efficiency, energy conversion, storage, and supporting infrastructure can reduce environmental burdens while improving the technical and economic performance of energy systems. The development of advanced materials and associated engineering solutions has been identified as an important mechanism for supporting the green transformation of the new-energy industry, especially where improvements in durability, conversion efficiency, and resource utilization can produce system-wide sustainability benefits (Yutong, 2025). Renewable technologies are also undergoing rapid technical development. Recent innovations in wind-power systems have focused on increasing conversion efficiency, strengthening grid integration, improving control strategies, and overcoming variability-related constraints, thereby expanding the potential contribution of wind generation to sustainable electricity systems (Elkelawy et al., 2025). At the same time, offshore energy development is increasingly being considered alongside carbon capture, utilization, and storage strategies as countries seek pathways that combine energy production with carbon-neutrality objectives (Xie, 2025).

Solar energy similarly provides substantial opportunities, although its effective integration depends on system configuration and regional conditions. Integrated solar and natural-gas combined-cycle power plants demonstrate how renewable and conventional technologies can be combined to improve overall energy performance, particularly in regions with high solar potential where hybridization may reduce fuel consumption while preserving generation reliability (Alfaris et al., 2025). Such hybrid configurations are important because the transition toward low-carbon generation rarely occurs through the immediate elimination of existing thermal infrastructure. Instead, conventional and renewable technologies frequently coexist during extended transition periods, making the sustainability performance of existing generating assets an important policy and management concern. This is particularly relevant in countries whose electricity supply remains strongly dependent on fossil-fuel-based thermal and combined-cycle plants.

Emerging renewable-energy applications also demonstrate the increasing complexity of energy-resource interactions. Variable renewable electricity can be used not only for direct electricity supply but also as an input into new industrial and biological production systems. Research into sustainable single-cell protein production based on variable

renewable electricity illustrates the broader potential for renewable power to support resource-efficient production pathways and sector coupling (Fasihi et al., 2025). Similarly, hydrogen is gaining importance as an energy carrier capable of linking renewable electricity to sectors in which direct electrification may be difficult. Reviews of hybrid proton-exchange-membrane fuel-cell power plants fueled by hydrogen in shipping show that hydrogen-based technologies can contribute to emission reduction and energy-system sustainability, although technical, infrastructural, economic, and fuel-supply challenges remain significant (Dall'Armi et al., 2023). These developments reinforce the need to examine sustainability through interconnected technological, environmental, and economic mechanisms.

The increasing penetration of distributed generation, storage technologies, hydrogen systems, and flexible demand has also changed the organizational structure of electricity systems. Virtual power plants represent an important example of this transition because they coordinate distributed renewable-energy sources, energy-storage systems, and controllable loads as an integrated operational entity. Such systems can contribute to grid formation, demand response, flexibility, and the management of intermittent generation, thereby improving the capability of electricity networks to accommodate higher shares of renewable energy (Liu et al., 2023). At a smaller spatial scale, hybrid wind-photovoltaic-hydrogen-storage microgrids illustrate how coordinated energy-management strategies can balance generation, storage, conversion, and consumption under changing operational conditions. Two-stage management based on receding-horizon optimization has demonstrated the importance of dynamically coordinating these components rather than managing each technology independently (Wang, 2022). Together, these studies indicate that sustainable energy management is fundamentally a problem of interaction, adaptation, and dynamic decision-making.

At the same time, the sustainability challenge extends beyond the operation of generating technologies to the management of physical assets and resource flows throughout their life cycles. The rapid deployment of electric vehicles and other new-energy technologies, for example, is creating substantial reverse-logistics requirements for retired batteries. Sustainable battery-recycling systems must simultaneously address environmental objectives, logistics costs, network configuration, recovery flows, and uncertainty. Multi-objective optimization of dynamic reverse-logistics networks for retired new-energy vehicle batteries illustrates the importance of considering environmental and economic objectives jointly when managing the material consequences of energy transition technologies (Mu et al., 2023). Similar concerns arise in sustainable infrastructure and construction, where decisions regarding materials, structural systems, energy performance, and life-cycle impacts increasingly require integrated digital and optimization approaches. Research on building information modeling-based sustainable structural design has shown that BIM can support the integration of sustainability criteria into design optimization, although methodological, interoperability, and implementation challenges remain (Afzal et al., 2023).

Sustainability problems in energy and infrastructure systems are therefore characterized by multiple interacting objectives, heterogeneous decision-makers, uncertainty, and feedback. Optimization approaches have made important contributions to addressing these problems. Sustainable supply-chain studies, for example, show that resilience and environmental performance must often be considered simultaneously with cost and service requirements. Hybrid optimization approaches developed for resilient and sustainable supply chains in perishable-food industries demonstrate how disruption risks, environmental impacts, network decisions, and economic considerations can be incorporated into a unified decision framework (Abbasian et al., 2023). Likewise, sustainable two-echelon supply-chain network design under traffic congestion and uncertainty shows that system performance can change substantially when operational constraints and uncertain conditions are explicitly incorporated into decision models (Babaei et al., 2022). Although these studies concern supply chains rather than electricity generation directly, their methodological implications are highly relevant: sustainability outcomes arise from the combined effects of resource limitations, operational decisions, disruptions, costs, and environmental consequences.

Spatial and policy considerations further complicate energy-system planning. Decisions concerning the location and development of major generation facilities must account for energy demand, environmental compatibility, infrastructure access, safety, and long-term policy objectives. Spatial evaluation of nuclear-power-plant installation has demonstrated the importance of integrating energy demand and sustainability criteria into strategic energy-policy decisions (Akar et al., 2023). At the organizational level, sustainability also depends on whether

firms and institutions actually adopt green behaviors. Agent-based research on construction enterprises has shown that green development behavior may emerge from interactions among organizational characteristics, external conditions, policies, and behavioral responses rather than from a single determinant (Li et al., 2022). These findings highlight an important limitation of purely static approaches: even when technically desirable policies are identified, their actual effects depend on how heterogeneous actors interpret, adopt, resist, or adapt to them over time.

Agent-based modeling (ABM) provides a particularly suitable framework for representing this type of complexity. Unlike models that treat an energy system as a homogeneous aggregate, ABM represents individual actors or technical entities as agents possessing their own attributes, states, decision rules, and capacities for interaction. System-level outcomes then emerge from repeated interactions among these heterogeneous components. Systematic research on agent-based approaches in multi-energy systems has shown that ABM is particularly valuable for investigating decentralized decision-making, technological heterogeneity, market behavior, consumer responses, policy interventions, and interactions across energy carriers (Yao et al., 2023). Because agents can respond differently to identical external conditions, ABM can reveal nonlinear and unintended outcomes that may remain hidden in aggregate models.

The computational development of ABM has also increased its applicability to large and complex systems. Parallel agent-based modeling environments and libraries differ in programmability, computational structure, and capacity for parallelization, making computational architecture an important consideration when simulations contain large populations or extensive interactions (Wang et al., 2022). More broadly, the value of ABM lies not merely in computational simulation but in its ability to translate conceptual relationships into explicit behavioral mechanisms. Variables such as generation capacity, equipment failure, maintenance decisions, resource availability, demand growth, regulatory pressure, and investment can be assigned to different agents and connected through dynamic rules. This permits researchers to examine how system-level sustainability changes as individual conditions, policies, and behavioral rules are modified.

Such an approach is highly relevant to power-generation sustainability because electricity systems contain multiple feedback loops. Improvements in generation efficiency can lower fuel requirements, reduce emissions per unit of electricity, decrease operating costs, and potentially improve profitability. Conversely, equipment aging may increase failure probability, reduce available capacity, increase maintenance requirements, and create supply shortages. Growing electricity demand can place additional pressure on generating assets and accelerate the consumption of fuel and water resources. Environmental regulations may reduce emissions but simultaneously increase costs when plants lack access to cleaner technologies or modernization finance. Technology subsidies may improve efficiency and environmental performance, but their effects depend on investment decisions and the operational characteristics of individual plants. These mechanisms cannot be adequately understood when technical, economic, resource, and environmental variables are analyzed independently.

The need for integrated modeling is especially pronounced in Iran. Renewable-energy policy research has emphasized that Iran possesses considerable renewable potential but continues to face significant policy, investment, institutional, infrastructural, and implementation challenges in achieving a more sustainable energy structure (Zahedi et al., 2022). The power sector must simultaneously address growing electricity requirements, the performance of existing thermal generation assets, fossil-fuel dependence, environmental pressures, investment requirements, and the expansion of renewable resources. Under such conditions, sustainability policy involves difficult trade-offs. A policy that improves one dimension may weaken another; for example, stricter environmental regulation may increase operating costs, while aggressive generation expansion may improve short-term supply adequacy but intensify fuel consumption, water use, and emissions. Consequently, policy evaluation requires a framework capable of tracing these effects across time and across multiple dimensions.

A further challenge is that sustainability cannot be separated from the resilience of existing generation infrastructure. Power plants operate under changing demand, equipment degradation, maintenance schedules, fuel constraints, water limitations, price conditions, and regulatory requirements. Their sustainability therefore depends not only on environmental performance but also on the ability to maintain reliable electricity output while absorbing operational and resource shocks. Conventional optimization models are useful for identifying efficient solutions under specified assumptions, but they may not fully represent heterogeneous equipment conditions, stochastic failures, adaptive responses, feedback loops, and interactions among producers, regulators, and electricity demanders. ABM can complement optimization by showing

how local decisions and constraints generate system-wide trajectories over time.

Moreover, sustainability-oriented decision support requires models that are sufficiently comprehensive to represent trade-offs while remaining interpretable for managers and policymakers. The literature increasingly demonstrates sophisticated optimization and modeling approaches for renewable integration, energy management, infrastructure location, supply-chain resilience, green behavior, and technological transition (Abbasian et al., 2023; Afzal et al., 2023; Akar et al., 2023). Nevertheless, these research streams often focus on specific technologies, sectors, optimization objectives, or policy instruments. Energy-transition studies emphasize diversification and low-carbon technologies (Beck, 2025; Gitelman et al., 2023), while renewable-system studies frequently concentrate on the integration and operational management of wind, solar, hydrogen, or storage technologies (Alfaris et al., 2025; Dall'Armi et al., 2023; Elkelawy et al., 2025). Agent-based energy research, in turn, provides a strong methodological basis for representing heterogeneous actors and dynamic interactions (Yao et al., 2023), but a need remains for context-sensitive models that connect plant-level technical conditions with economic performance, environmental consequences, critical-resource constraints, electricity demand, and regulatory intervention.

Addressing this gap is particularly important for Iranian power generation, where existing generating plants remain indispensable to supply security while the broader energy system moves toward greater sustainability. A useful decision-support framework must therefore capture the relationships among equipment efficiency, capacity, reliability, failures and maintenance, fuel and water consumption, emissions, operating costs, revenues, profitability, electricity-demand growth, and policy instruments. It must also make it possible to compare alternative interventions rather than assuming that one-dimensional improvement automatically produces system-wide sustainability. By combining expert-derived sustainability dimensions with agent-based simulation, such a framework can translate qualitative knowledge about power-plant operations into explicit agents, variables, behavioral rules, constraints, and feedback mechanisms and can subsequently test how alternative technical, resource, economic, and regulatory scenarios reshape sustainability over time.

Accordingly, the aim of this study is to develop and evaluate a comprehensive agent-based sustainability model for Iran's power-generation industry that dynamically integrates technical-operational, economic, environmental, resource, institutional-policy, and demand-related interactions and supports the assessment of alternative management and policy scenarios.

2. Methods and Materials

The research is applied in purpose and exploratory mixed-method in design. The methodological logic is sequential: qualitative evidence is first used to identify the dimensions, components, and causal relationships of power-plant sustainability; the resulting knowledge structure is then translated into agents, state variables, and behavioral rules in an ABM environment.

The expert panel comprised 25 specialists from the power-generation, energy, and sustainability domains. Purposive sampling was used to ensure coverage of technical, economic, environmental, systems, and policy perspectives. The panel included power and plant-operation engineers, mechanical and thermal-equipment specialists, industrial and systems engineers, energy and environmental experts, energy-policy managers, and academic researchers. Eleven participants held doctoral degrees and fourteen held master's degrees; eighteen had more than ten years of professional experience.

Data collection combined a structured review of scientific literature with semi-structured expert interviews. The interview data were analyzed using thematic analysis. Initial coding was followed by the identification of basic themes, organizing themes, and global themes. To improve credibility and dependability, theme summaries were reviewed by experts, the coding trail and merge/split decisions were documented, 20% of the material was independently recoded, and the resulting inter-coder agreement coefficient was 0.84. Thematic saturation was reached in the final interviews.

The thematic results were then operationalized in Net-Logo. Each principal component of the system was represented as an agent or model state with explicit decision rules. Operational parameters were calibrated using plant documentation, performance reports, engineering assumptions, and expert judgments. Because equipment failure is stochastic, scenario comparisons should be based on repeated runs; the recommended design is at least 30 independent replications per scenario with reporting of means, standard deviations, and 95% confidence intervals.

Table 1

Expert-panel composition.

Dimension	Category	n	%
Expertise	Power engineering / plant operation	6	24
Expertise	Mechanical / thermal equipment	5	20
Expertise	Industrial engineering / systems	5	20
Expertise	Energy and environment	4	16
Expertise	Energy management / policy	3	12
Expertise	Academic sustainability research	2	8
Education	PhD	11	44
Education	MSc	14	56
Experience	5–10 years	7	28
Experience	10–15 years	9	36
Experience	>15 years	9	36

The thematic analysis transformed 487 meaningful statements into 112 initial codes, 36 basic themes, 12 organizing themes, and six global themes. Technical-operational sustainability received the highest expert coverage (96%), followed by environmental (92%), economic (88%), resource (84%), institutional-policy (80%), and social-human sustainability (72%). Coverage represents the proportion of experts who made at least one meaningful reference to the theme and should not be interpreted as a final statistical weight.

Table 2

Global sustainability themes identified through thematic analysis.

Global theme	Expert coverage	Representative components	Operational ABM linkage
Technical and operational	96%	Efficiency, capacity, availability, failures, preventive maintenance	capacity, efficiency, availability, failure-probability
Environmental	92%	CO2 emissions, emission intensity, environmental compliance	emission, carbon-factor, emission-limit
Economic	88%	Fuel cost, operating cost, maintenance, revenue, profit	fuel-cost, operating-cost, total-cost, revenue profit
Resources	84%	Fuel security, water management, resource efficiency	fuel-availability, water-availability, fuel-consumption, water-use
Institutional and policy	80%	Carbon tax, penalties, subsidies, policy coordination	carbon-tax, penalty-rate, subsidy-renewable
Social and human	72%	Skills, safety, service reliability, stakeholder trust	unmet-demand, supply-adequacy; indirectly represented

Technical-operational sustainability was interpreted as the plant's ability to generate electricity reliably, continuously, and efficiently under changing demand, aging equipment, and operating constraints. Experts emphasized that environmental or economic policies cannot be considered sustainable if they undermine reliable generation. Efficiency was therefore treated as a linking variable because lower efficiency increases fuel consumption, variable cost, and emissions per unit of electricity.

Economic sustainability was defined as the plant's ability to cover fuel, operation, maintenance, and environmental-compliance costs while maintaining sufficient cash flow for continuity and modernization. Environmental sustainability focused on total and specific emissions, compliance, clean technology, and the distinction between genuine emission-intensity improvement and emission reduction caused merely by lower generation. Resource sustainability captured secure and efficient water and fuel supply. Institutional-policy sustainability represented the consistency of regulation and the combined influence of taxes, limits, penalties, and technology incentives. Human and social factors were retained conceptually because skills, safety culture, and technology acceptance affect the success of maintenance and modernization policies.

The ABM contains three principal agent types: power plants, a regulator, and electricity demanders. Power-plant agents hold technical, economic, environmental, and resource states. The regulator applies carbon taxes, emission

limits, penalties, and technology subsidies. The demander updates electricity demand over time. Their interaction follows a recurring cycle: demand is updated; plant failures are realized; active units choose production subject to capacity and resource constraints; fuel and water are consumed; emissions and policy costs are computed; revenues and profits are updated; and resource stocks and sustainability indicators are recalculated.

Table 3

Core equations and behavioral meaning of the agent-based model

Model component	Equation / rule	Interpretation
Generation decision	P_i(t) = min[Capacity_i, Demand/N_active, FuelLimit_i, WaterLimit_i]	Production is simultaneously constrained by capacity, active-unit demand share, fuel, and water.
Fuel consumption	Fuel_i(t) = P_i(t) / Efficiency_i	Less efficient units consume more fuel for the same output.
Water use	WaterUse_i(t) = 0.5 × P_i(t)	Water consumption increases linearly with production in the current model.
Emissions	Emission_i(t) = Fuel_i(t) × CarbonFactor_i	Emissions depend on fuel use and emission factor.
Demand	D(t) = D(t−1) × (1+g) × PriceEffect	Demand evolves dynamically with growth and price sensitivity.
Total cost	FuelExpense + OpExpense + EnvironmentalCost + CarbonTax + Penalty + Maintenance	Technical efficiency and regulation jointly affect total cost.
Revenue	ElectricityPrice × P_i(t) + SubsidyIncome_i	Revenue is primarily driven by delivered generation.
Profit	Revenue_i − TotalCost_i	Economic sustainability is an emergent outcome of technical and policy conditions.

The baseline simulation used five power-plant agents, one regulator, and one demander. Initial water availability was 100,000 model units, initial fuel availability was 150,000 units, electricity price was 85 monetary units, annual demand growth was 3%, and the maximum horizon was 120 ticks. Heterogeneity was introduced through unit-specific capacity, efficiency, technology level, age, and stochastic failure probability. Because the current resource-depletion structure can terminate a run before the nominal horizon, premature stopping is itself interpreted as evidence of long-term resource stress rather than as a numerical failure.

Eight scenarios were evaluated: (S1) baseline conditions; (S2) high demand growth; (S3) increased fuel price; (S4) stricter carbon policy; (S5) technology and efficiency upgrading; (S6) water shortage; (S7) fuel shortage and supply decline; and (S8) an integrated policy combining controlled demand growth, technological upgrading, preventive maintenance, balanced carbon regulation, technology support, and improved water and fuel security.

3. Findings and Results

The thematic analysis showed that Technical and Operational Sustainability, with 96% coverage, received the highest level of expert agreement. Experts emphasized continuity of electricity generation, efficiency improvement, equipment reliability, and unit availability as prerequisites for the other sustainability dimensions. Environmental Sustainability (92%) and Economic Sustainability (88%) ranked next. Resource, institutional-policy, and social-human considerations were also retained because the interviews indicated strong cross-dimensional effects.

Figure 1

Frequency of Expert Emphasis on the Global Sustainability Themes

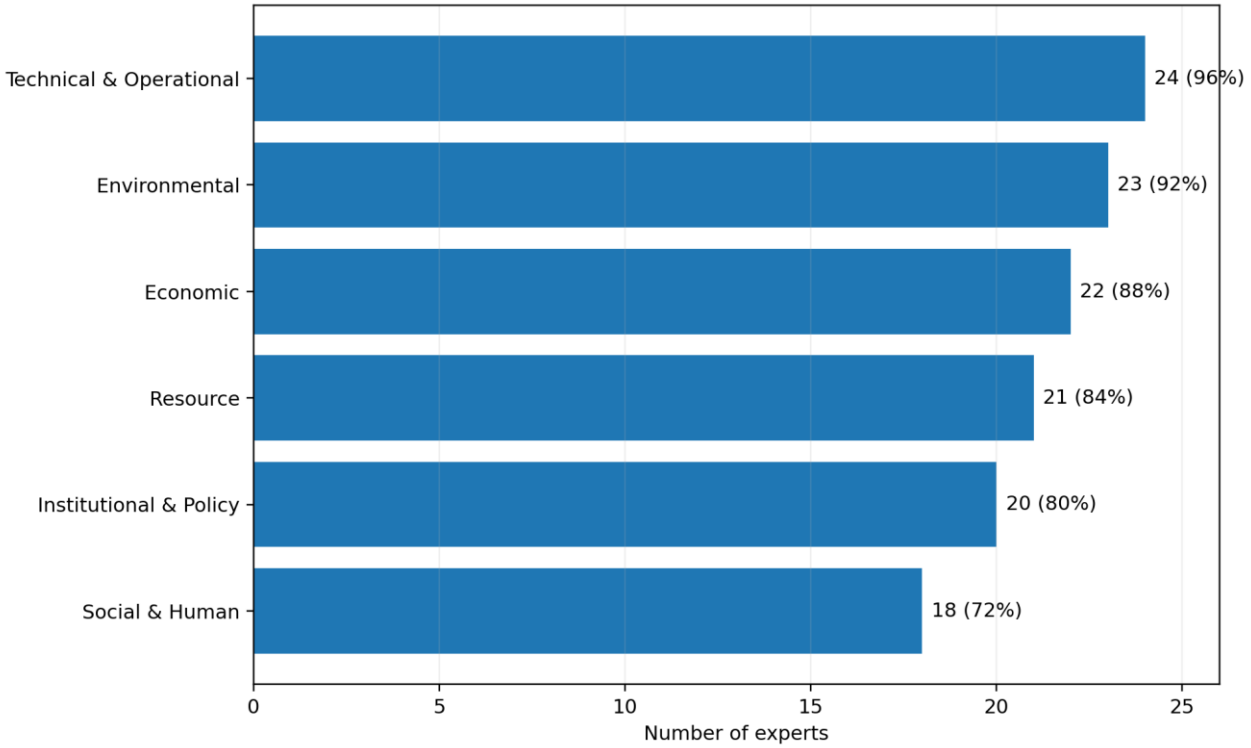
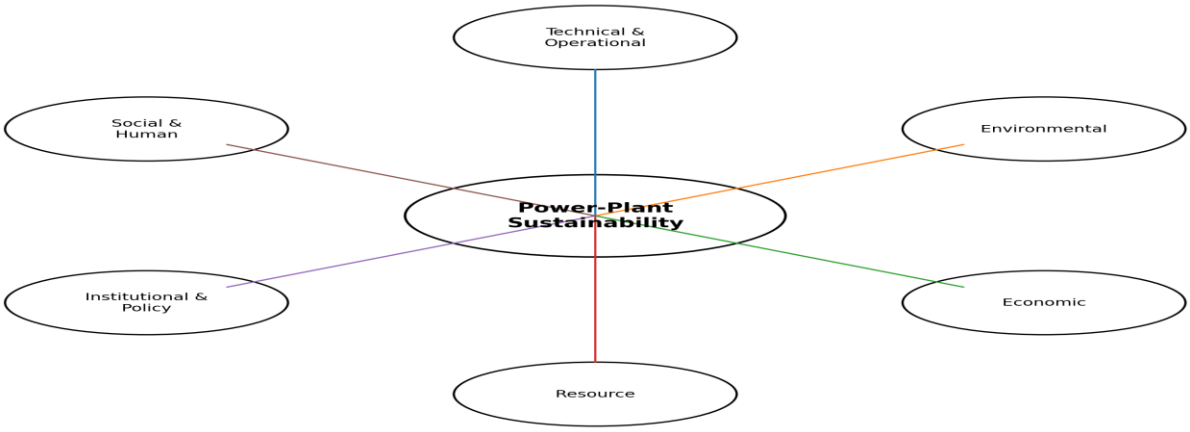


Figure 2

Relationship Map of the Global Themes of Power-Plant Sustainability



Technical and operational sustainability refers to the ability of a power plant to generate electricity reliably, continuously, and efficiently under changing demand, equipment aging, and operational constraints. Experts emphasized that environmental or economic policies cannot be considered sustainable in practice if they compromise generation reliability. This global theme was represented through production efficiency, equipment reliability, maintenance, and modernization. The interpretation of the findings showed that efficiency is not merely a technical indicator; rather, it links the economic, environmental, and resource dimensions. Lower efficiency increases fuel

consumption, variable cost, and emissions per unit of electricity generated. Accordingly, the agent-based model uses efficiency as a direct determinant of fuel consumption, emissions, costs, and profit. Equipment failures are represented as stochastic events, while repair time is modeled dynamically to reproduce fluctuations in availability and supply shortages.

Economic sustainability refers to the power plant's ability to cover generation, maintenance, and environmental-compliance costs while maintaining sufficient financial flows for continued operation and modernization. Experts identified tariff instability, increasing fuel costs, maintenance expenses, and investment constraints as major threats. In the model, this theme is represented by fuel cost, operating cost, maintenance cost, carbon-tax cost, penalties, subsidies, revenue, and profit. A key qualitative finding was that increasing carbon taxation without a supporting modernization mechanism may improve environmental incentives while weakening economic sustainability. Therefore, the regulator agent simultaneously uses taxation, penalties, and technology subsidies.

Resource sustainability concerns the reliable supply and efficient use of water and fuel. Water scarcity under Iran's climatic conditions and the dependence of thermal power plants on fossil fuels make this theme an operational bottleneck. The findings indicate that resources should not be modeled merely as initial stocks because, in reality, fuel and water are replenished periodically. Accordingly, the final conceptual specification includes periodic fuel- and water-supply variables, enabling simulation of gradual shortages and supply disruptions.

Institutional and policy sustainability refers to the quality of rules, inter-institutional coordination, and the capacity of policies to influence agent behavior. Experts stressed that isolated and inconsistent policies such as carbon taxation without tariff reform, or mandatory generation without secure fuel supply can create new conflicts. In the agent-based model, the regulator agent represents this dimension through carbon-tax, emission-limit, penalty-rate, and subsidy-renewable variables. The combined-policy scenario directly reflects the theme of policy coordination.

Although the initial computational version of the model primarily focuses on technical, economic, environmental, and resource dimensions, the thematic analysis showed that human and social factors are prerequisites for successful policy implementation. Employee skills, safety culture, technology acceptance, employment, and service quality were important components. In the current model, part of the social dimension is represented indirectly through reliability, electricity shortages, preventive maintenance, and technology level. Future extensions may introduce employee or local-community agents and directly simulate accident rates, skills, satisfaction, and employment.

Table 4

Mapping of Themes and Sample Codes to Model Variables.

Dimension	Basic theme / indicator	Operational definition	Model variable
Technical	Generation efficiency	Ratio of energy output to fuel input	efficiency
Technical	Available capacity	Maximum reliable generation in a period	capacity / available-capacity
Technical	Availability	Proportion of time the unit is ready for operation	availability
Technical	Failure rate	Probability of forced unit outage	failure-probability / failure-rate
Technical	Repair time	Time required to return the unit to service	remaining-repair-time
Economic	Fuel cost	Fuel-consumption cost in each period	fuel-cost
Economic	Operating cost	Variable generation cost	operating-cost
Economic	Maintenance cost	PM and failure-repair cost	maintenance-cost
Economic	Electricity sales revenue	Generation multiplied by selling price	revenue
Economic	Profit	Revenue minus total cost	profit
Environmental	Total emissions	Periodic emissions from all power plants	total-emission
Environmental	Emission intensity	Emissions per unit of generation	emission-intensity
Environmental	Emission limit	Permissible level determined by the regulator	emission-limit

Resource	Fuel consumption	Fuel required according to output and efficiency	fuel-consumption
Resource	Water consumption	Water use proportional to output	water-use
Resource	Fuel availability	Available system fuel stock	fuel-availability
Resource	Water availability	Available system water stock	water-availability
Policy	Carbon tax	Emission-based cost	carbon-tax
Policy	Excess-emission penalty	Cost of exceeding the permissible limit	penalty-rate
Policy	Technology subsidy	Support for technology and efficiency	subsidy-renewable
Demand / Social	Demand growth	Annual increase in electricity consumption	annual-demand-growth
Demand / Social	Unmet demand	Gap between demand and generation	unmet-demand
Demand / Social	Supply adequacy	Ratio of generation to demand	supply-adequacy

The thematic analysis was not limited to listing factors. Several important causal relationships and feedback loops were extracted from the interviews and used as the basis for the calculation sequence and behavioral rules of the agent-based model.

Table 5

Relationships Between Themes and Extracted Causal Loops.

No.	Conceptual relationship	Type of effect
1	Higher efficiency → lower fuel consumption → lower cost and emissions	Desirable reinforcing effect
2	Aging → higher failure probability → lower supply → greater shortage	Undesirable reinforcing effect
3	Preventive maintenance → fewer failures → higher availability	Balancing effect
4	Demand growth → pressure on capacity and resources → higher emissions and shortages	Undesirable reinforcing effect
5	Carbon tax → higher cost → technology incentive or lower profit	Dual / dependent on complementary policy
6	Water or fuel shortage → generation constraint → lower revenue and supply adequacy	Bottleneck effect
7	Technology subsidy → higher efficiency → simultaneous improvement in multiple dimensions	Desirable reinforcing effect
8	Policy coordination → fewer cross-dimensional conflicts → higher overall sustainability	Integrated effect

The most important implication of these relationships is that power-plant sustainability is a nonlinear, multi-bottleneck problem. For example, increasing generation capacity without securing adequate resources, or imposing emission restrictions without enabling technology investment, does not necessarily improve sustainability. This logic provides the principal rationale for using agent-based modeling in the subsequent stage of the research.

The baseline reconstruction reveals a pronounced mismatch between average demand and supply. Average demand was approximately 8,172.38 model units, whereas average supply was 2,800.03 units, producing an average unmet demand of 5,372.35 units and an average supply-adequacy level of 34.78%. The result demonstrates that demand growth cannot be translated into unlimited generation because capacity, failures, fuel, and water act as sequential constraints.

Fuel consumption is inversely related to unit efficiency. With individual efficiencies distributed approximately between 0.35 and 0.55, lower-efficiency plants consume disproportionately more fuel and accelerate both stock depletion and emissions. In the reported baseline run, the initial fuel stock of 150,000 units was eventually exhausted. Water use was modeled as proportional to electricity generation; approximately 68% of the initial water stock remained at the end of the reconstructed run, indicating that fuel became the binding resource earlier than water.

Emissions directly follow fuel use. The first-period total emission was approximately 5,484.22 units, while the mean of the final periods was about 4,564.62 units. A lower final emission value should not automatically be interpreted as environmental improvement because the model shows that emissions may fall as a consequence of reduced generation caused by resource scarcity or failures. For this reason, emission intensity is conceptually more informative than total emissions alone.

Economic outputs also reflect the interaction of technology, resources, and policy. Total first-period cost was

approximately 264,832.85 monetary units, while first-period revenue and profit were about 283,780.00 and 18,947.15 units, respectively. By the end of the reported run, profit fell to approximately 5,571.29 units. The economic sustainability score was 54.71, illustrating that profitability deteriorates as supply becomes constrained and carbon- and environment-related costs accumulate.

Table 6

Selected baseline simulation outcomes.

Indicator	Initial / early value	Final / reported value	Interpretation
Electricity demand	5,150.0 after first update	9,301.5	Exponential growth pressure
Electricity supply	3,338.0	694.9	Constrained by failures and resources
Supply adequacy	64.8%	7.5%	Declining ability to satisfy demand
Total emissions	5,484.2	1,109.8	Lower final emissions partly reflect lower production
System profit	18,947.1	5,571.3	Economic deterioration under constraints
Remaining water	98,331.0	67,998.9	Gradual resource depletion
Remaining fuel	142,165.4	0.0	Binding resource constraint
Overall sustainability	56.0	56.4	Composite score masks internal imbalance

The thematic-analysis results showed that sustainability in the power-plant industry is not a one-dimensional phenomenon; rather, it emerges from the simultaneous interaction of economic, technical, environmental, resource-related, technological, and institutional factors. Accordingly, the agent-based model was designed to represent the independent and heterogeneous behavior of power plants, the regulatory authority, and electricity demanders over time, rather than treating the power-plant industry as a homogeneous integrated system. The main advantage of this approach is that macro-level sustainability outcomes emerge from agents' micro-level decisions, constraints, and interactions. Consequently, the model can analyze nonlinear behavior, critical thresholds, time delays, and unintended policy effects.

The thematic analysis identified plant efficiency, equipment aging, reliability, preventive maintenance, fuel price, electricity-sales revenue, water constraints, fuel constraints, carbon emissions, environmental taxes and penalties, government support, technological investment, and demand growth as the principal factors affecting sustainability. These themes were converted into three modeling elements: agents, state variables, and behavioral rules. Therefore, each model variable has a conceptual basis in the thematic analysis and was not introduced merely for software-related reasons.

Table 7

Correspondence between Themes, Components, and Agent-Based Model Elements.

Main Theme	Extracted Components	Agent	Model Variables
Technical sustainability	Efficiency, capacity, availability, failure, repair time	Power-plant agent	efficiency, capacity, availability, failed?, repair-time
Economic sustainability	Fuel cost, operating cost, revenue, profit, subsidy	Power plant and regulator	fuel-cost, operating-cost, revenue, profit, subsidy
Environmental sustainability	Fuel consumption, carbon factor, emissions, tax and penalty	Power plant and regulator	emission, carbon-factor, carbon-tax, penalty
Resource sustainability	Water/fuel stocks and supply, consumption intensity	System environment and power plant	water-availability, fuel-availability, intensities
Demand growth and pressure	Initial demand, growth rate, electricity shortage	Demander agent	demand-level, demand-growth, unmet-demand
Technology and innovation	Technology level, efficiency improvement, emission reduction	Power plant and policymaker	technology-level, upgrade, emission-reduction
Governance and policy	Emission limit, carbon tax, penalty, subsidy	Regulator agent	emission-limit, carbon-tax, penalty-rate, subsidy

The model consists of three types of agents. The first is the power-plant agent, which stores technical, economic, and environmental decisions and states. Each plant has its own capacity, efficiency, age, technology level, failure

probability, fuel consumption, water consumption, emissions, costs, revenue, and profit. This heterogeneity means that two plants with equal nominal capacity may generate different sustainability outcomes because of differences in age, efficiency, or technology.

The second agent is the regulator, which implements public policies including carbon taxation, permissible emission limits, penalty rates, and technology subsidies. The third agent is the electricity demander, which updates demand according to annual growth. Their interaction creates the main model cycle: demand increases; power plants generate according to capacity, failure status, and available resources; generation consumes water and fuel and produces emissions; the regulator imposes policy-related costs; and sustainability indicators are then calculated.

Table 8

Baseline Settings and Model Calibration.

Parameter	Baseline Value	Selection Logic
Number of power plants	5 agents	Represents heterogeneity at a manageable scale
Simulation horizon	120 months	Equivalent to 10 years
Initial demand	5,000 units	Common basis for scenario comparison
Baseline annual demand growth	3%	Gradual rather than explosive growth
Electricity price	85 monetary units	Maintains the possibility of baseline profitability
Fuel cost	18 units	Basis for the fuel-price shock scenario
Carbon tax	10 units	Moderate environmental policy
Initial water stock	150,000 units	Operational reservoir and model stock
Initial fuel stock	300,000 units	Supports execution across the nominal horizon
Recommended replications	30–50 runs	Controls variability arising from stochastic failures

This section analyzes the dynamic behavior of the agent-based model developed for Shahid Montazer Ghaem Power Plant on the basis of three principal agents: the power plant, regulator, and demand agent. The model structure is supported by the thematic-analysis findings. Technical and operational sustainability, economic sustainability, environmental sustainability, resource and infrastructure management, governance and policymaking, and human capital were translated into simulatable variables. In the NetLogo code, capacity, efficiency, failure probability, fuel and water consumption, emissions, costs, revenue, profit, carbon taxation, and supply adequacy form the system's principal feedback loops.

The reconstructed baseline simulation used five power-plant agents, one regulator, one demand agent, initial water resources of 100,000 units, initial fuel resources of 150,000 units, an electricity price of 85, demand growth of 3%, and a maximum horizon of 120 ticks. Because of rapid resource consumption and the model's stopping condition, the reconstructed run terminated before the nominal horizon. This is itself an important model finding: demand growth combined with limited efficiency and linear resource consumption threatens long-term system sustainability.

The simulation integrates electricity generation, fuel consumption, water use, pollutant emissions, electricity demand, operating costs, revenue, and profit within a unified decision framework. The electricity-generation decision function is defined as:

$P_i(t) = \min[Capacity_i, Demand(t)/N_active, FuelLimit_i, WaterLimit_i]$

This multi-constraint decision rule distributes electricity demand among active generating units and subsequently restricts the output of each unit according to nominal capacity, allocated demand, fuel availability, and water availability. Consequently, increasing electricity demand does not necessarily lead to a proportional increase in electricity supply. In the earlier stages of the simulation, installed capacity and equipment failures constitute the primary generation constraints, whereas fuel and water availability become progressively more influential as resource stocks decline. The results therefore demonstrate the importance of equipment reliability management, operational resilience, load flexibility, and fuel-supply security in maintaining sustainable electricity generation.

Table 9

Integrated Results of the Power-Plant Sustainability Simulation

Function / Dimension	Variable or Indicator	Approximate Value
Electricity Generation	Average supply	2,800.03
Electricity Generation	Average demand	8,172.38
Electricity Generation	Average unmet demand	5,372.35
Electricity Generation	Average supply adequacy	34.78%
Fuel Consumption	Average fuel consumption in final periods	6,520.88
Fuel Consumption	Average plant efficiency	43.83%
Fuel Consumption	Initial fuel stock	150,000.00
Fuel Consumption	Remaining fuel stock	0.00
Water Consumption	Average water consumption in final periods	1,400.01
Water Consumption	Initial water stock	100,000.00
Water Consumption	Remaining water stock	67,998.87
Water Consumption	Remaining water	68.00%
Pollutant Emissions	Total emissions in the first period	5,484.22
Pollutant Emissions	Average emissions in final periods	4,564.62
Pollutant Emissions	Cumulative emissions at model termination	105,000.00
Pollutant Emissions	Environmental sustainability score at model termination	77.80
Electricity Demand	Defined initial demand	5,000.00
Electricity Demand	Demand after the first update	5,150.00
Electricity Demand	Demand at model termination	9,301.47
Electricity Demand	Cumulative demand growth	86.03%
Power-Plant Cost	Total cost in the first period	264,832.85
Power-Plant Cost	Average cost in final periods	220,619.99
Power-Plant Cost	Average revenue in final periods	238,052.29
Power-Plant Cost	Cost-to-revenue ratio at model termination	90.58%
Power-Plant Revenue	Total revenue in the first period	283,780.00
Power-Plant Revenue	Average revenue in final periods	238,052.29
Power-Plant Revenue	Revenue at model termination	59,120.69
Power-Plant Revenue	Electricity price	85.00
Power-Plant Profit	Profit in the first period	18,947.15
Power-Plant Profit	Average profit in final periods	17,432.31
Power-Plant Profit	Profit at model termination	5,571.29
Power-Plant Profit	Economic sustainability score at model termination	54.71

Fuel consumption is determined according to the function $Fuel_i(t) = P_i(t) / Efficiency_i$, indicating an inverse relationship between plant efficiency and fuel requirements. Accordingly, two generating units producing the same quantity of electricity may consume substantially different amounts of fuel when their efficiencies differ. Because unit efficiency in the model varies approximately between 0.35 and 0.55, lower-efficiency units impose disproportionately greater pressure on fuel resources and also generate higher pollutant emissions. The average plant efficiency was 43.83%, while average fuel consumption during the final periods reached 6,520.88. More importantly, the entire initial fuel stock of 150,000.00 was depleted by the end of the simulation. This result identifies fuel availability as one of the most critical long-term constraints on electricity-generation sustainability.

Water use is represented by $WaterUse_i(t) = 0.5 \times P_i(t)$, meaning that water consumption changes directly in proportion to electricity output. Under this simplifying assumption, increases in generation progressively reduce available water resources and may eventually impose an additional ceiling on generation. Average water consumption in the final periods was 1,400.01, while the water stock declined from an initial value of 100,000.00 to 67,998.87 at model termination. Thus, approximately 68.00% of the initial water stock remained available. Compared with fuel, water was therefore not exhausted during the simulation; however, the results confirm that persistent increases in electricity generation would progressively intensify pressure on water resources.

Pollutant emissions are determined through $Emission_i(t) = Fuel_i(t) \times CarbonFactor_i$. Since the carbon factor is fixed at 0.70 across generating units, differences in unit-level

emissions arise primarily from differences in electricity production and efficiency. Total emissions amounted to 5,484.22 in the first period, while average emissions during the final periods were 4,564.62. Cumulative emissions reached 105,000.00 by model termination. Despite these emissions, the environmental sustainability score at termination was 77.80. The results indicate that improvements in generating efficiency can simultaneously reduce fuel depletion and pollutant emissions and therefore represent an important leverage point for improving environmental performance.

Electricity demand follows the relationship $D(t) = D(t-1) \times (1 + g) \times \text{PriceEffect}$. In the baseline scenario, demand increases by 3% at every simulation tick, while the electricity price remains constant and the price-sensitivity effect therefore remains equal to one. As a result, electricity demand grows approximately exponentially. Demand increased from an initial value of 5,000.00 to 5,150.00 after the first update and reached 9,301.47 at model termination, corresponding to cumulative growth of 86.03%. In contrast, average electricity supply was only 2,800.03, compared with average demand of 8,172.38. Consequently, average unmet demand reached 5,372.35 and average supply adequacy was only 34.78%. This substantial supply-demand imbalance demonstrates that demand growth cannot be accommodated when generation is simultaneously constrained by unit capacity, equipment reliability, and resource availability.

The economic subsystem further demonstrates the interconnected nature of technical, environmental, and financial performance. Total plant cost is defined as $\text{TotalCost}_i = \text{FuelExpense}_i + \text{OpExpense}_i + \text{EnvironmentalCost}_i + \text{CarbonTax}_i + \text{Penalty}_i + \text{MaintenanceCost}_i$. Thus, generation cost depends not only on electricity output but also on technological efficiency, maintenance requirements, environmental performance, and regulatory policies. A low-efficiency generating unit consumes more fuel for the same electricity output and consequently incurs higher fuel expenses, pollutant emissions, environmental costs, and carbon-tax liabilities. Total cost was 264,832.85 in the first period, while average cost in the final periods was 220,619.99. The cost-to-revenue ratio reached 90.58% at model termination, indicating substantial pressure on the economic margin of the simulated power-plant system.

Revenue is calculated as $\text{Revenue}_i(t) = \text{ElectricityPrice} \times P_i(t) + \text{SubsidyIncome}_i$. With the electricity price fixed at 85.00, generation volume remains the principal determinant of revenue, while technology-related subsidies provide only an additional contribution. Total revenue was 283,780.00 in the first period and average revenue during the final periods was 238,052.29. However, revenue declined sharply to 59,120.69 at model termination as generation was increasingly restricted by failures and resource shortages. These results demonstrate that revenue sustainability depends directly on maintaining generating capacity, fuel security, water availability, and plant reliability.

The final economic outcome is represented by $\text{Profit}_i(t) = \text{Revenue}_i(t) - \text{TotalCost}_i(t)$. Profit therefore reflects the combined effects of generation, fuel consumption, efficiency, equipment failures, electricity pricing, environmental regulation, and resource availability. Profit amounted to 18,947.15 in the first period and averaged 17,432.31 during the final periods, but decreased to 5,571.29 at model termination. The corresponding economic sustainability score was 54.71. The reduction in profitability demonstrates that increasing production alone cannot guarantee favorable economic performance because additional generation simultaneously increases fuel consumption, emissions, environmental costs, and carbon-tax liabilities.

Overall, the integrated results show that sustainable power-plant management cannot be based on optimization of a single variable. Electricity demand, electricity generation, efficiency, fuel consumption, water consumption, emissions, costs, revenues, and profits interact through reinforcing and balancing feedback mechanisms. Increasing demand places pressure on generation, higher generation accelerates fuel and water use, lower efficiency raises both resource consumption and emissions, and environmental and carbon-related costs subsequently reduce profitability. The model therefore identifies efficiency improvement, equipment reliability, demand management, fuel-supply security, water-resource management, and environmental-cost control as interconnected leverage points for improving power-plant sustainability.

For application to Shahid Montazer Ghaem Power Plant, the simulation parameters should be calibrated using actual unit-level generating capacity, outage and failure records, thermal efficiency, specific fuel consumption, fuel availability, water-use coefficients, maintenance expenditures, environmental costs, electricity prices, and operational revenues. Such calibration would enable the integrated model to be used for systematic comparison of alternative operational and policy scenarios and for identifying interventions capable of simultaneously

improving technical reliability, environmental sustainability, resource security, and economic performance.

Figure 3

Electricity Supply and Demand Trend under the Baseline Scenario

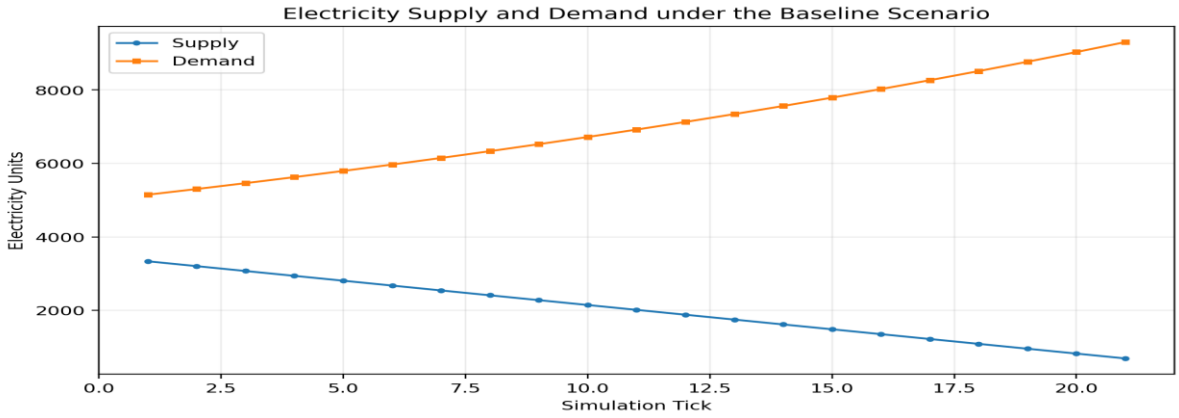


Figure 4

Carbon Dioxide Emission Trend under the Baseline Scenario

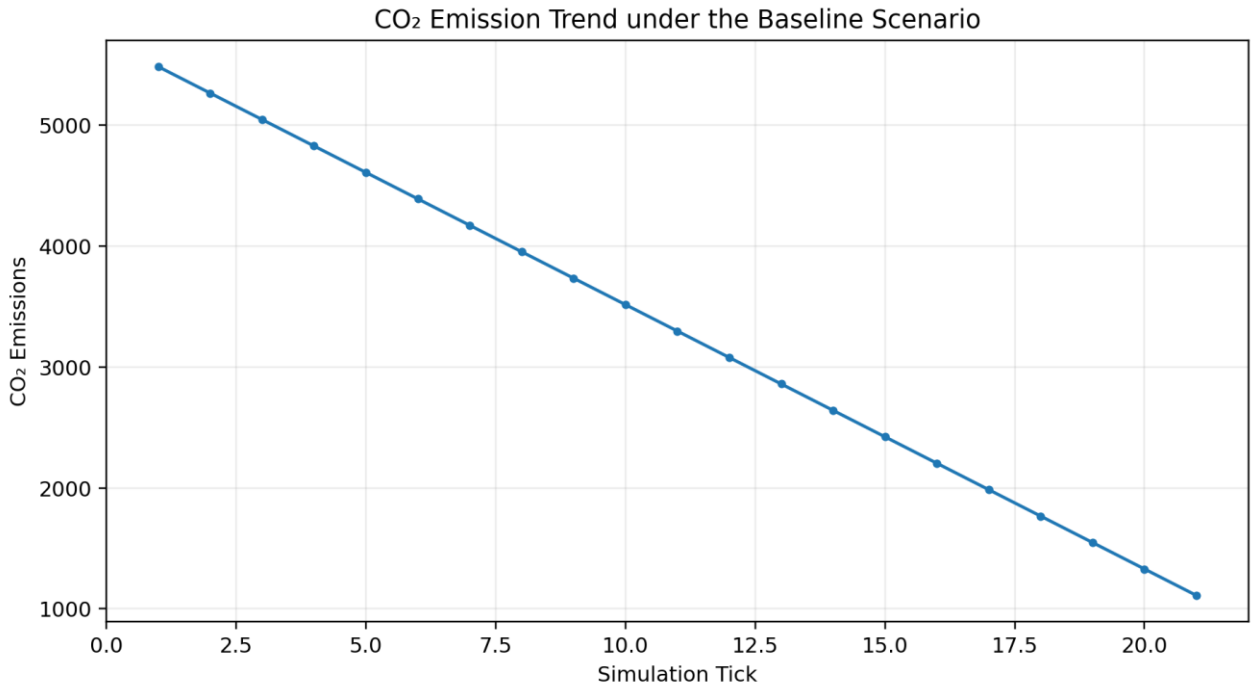


Figure 5

Total System Profit Trend under the Baseline Scenario

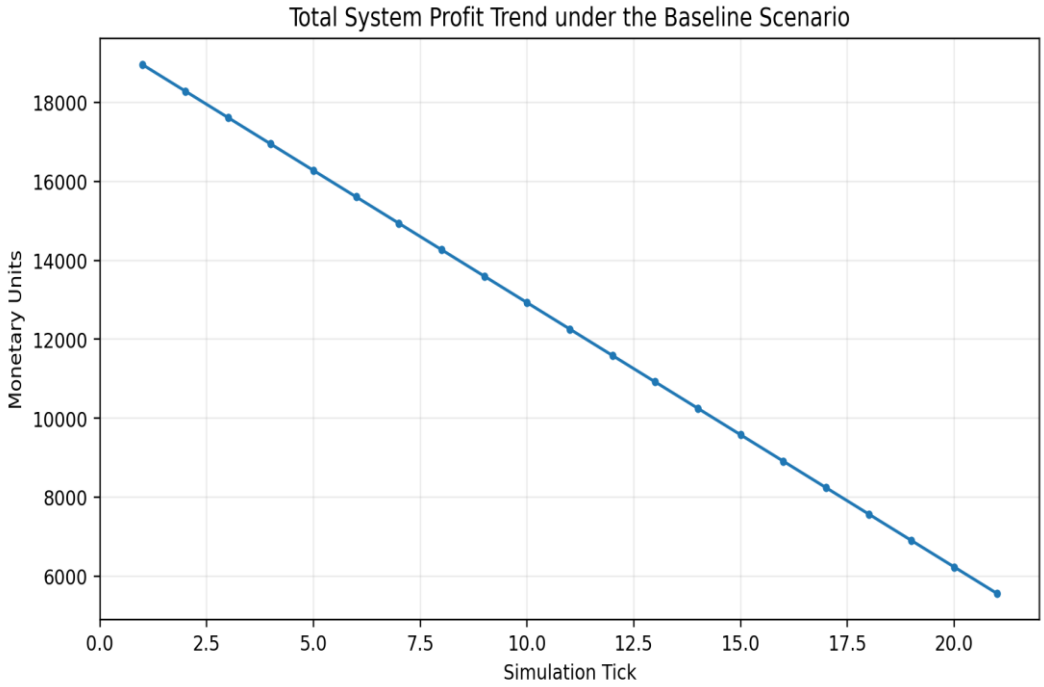


Table 10

Overall Analysis of Agent-Based Modeling Results.

Indicator	Beginning of Simulation	End of Model Run	Interpretation
Electricity demand	5,150.0	9,301.5	Increasing trend caused by exponential demand growth
Electricity supply	3,338.0	694.9	Constrained by capacity, failures, and resource stocks
Supply adequacy	64.8%	7.5%	Declining system responsiveness to growing demand
Total emissions	5,484.2	1,109.8	Dependent on generation, efficiency, and carbon factor
System profit	18,947.1	5,571.3	Affected by revenue and fuel/environmental costs
Remaining water	98,331.0	67,998.9	Linear decline proportional to generation
Remaining fuel	142,165.4	0.0	Faster decline in less-efficient units
Overall sustainability index	56.0	56.4	Composite of economic, environmental, technical, and resource dimensions

S1: Baseline. Demand increased from 5,000 to approximately 5,480 units in the scenario-oriented run, final supply was about 4,822 units, and supply adequacy was 88%. The final unmet demand was about 658 units. The overall sustainability score was 58, indicating a moderate condition with insufficient resilience against demand, fuel, or resource shocks.

S2: High demand growth. Increasing annual demand growth from 3% to 6% raised final demand to about 6,800 units, while final supply was around 4,896 units. Supply adequacy declined to 72% and the final shortage increased to roughly 1,904 units. The overall sustainability score fell to 45. This scenario confirms that a production-only response to demand growth, without simultaneous capacity

and efficiency improvements, weakens technical and environmental sustainability.

¬S3: Higher fuel price. Raising fuel cost from 18 to 30 monetary units left physical supply adequacy close to 86% because the current behavioral structure obliges plants to continue producing despite declining profitability. However, cumulative profit dropped from about 12,000 to 3,200 units, a decline of approximately 73.3%. This result shows that a fuel-price shock is primarily economic unless plant decisions are explicitly linked to fuel substitution, profit thresholds, or technology investment.

S4: Stricter carbon policy. A stronger carbon tax, a higher excess-emission penalty, and a lower emission limit reduced cumulative emissions from about 440,000 to 390,000 units, an improvement of approximately 11.4%. The environmental sustainability score rose from 52 to 78, but cumulative profit fell to about 7,500 units. The scenario creates an economy–environment trade-off unless carbon revenues are recycled into modernization and efficiency improvements.

S5: Technology and efficiency upgrading. Technology upgrading increased mean efficiency from approximately 41% to 52% and availability from 88% to 94%. Supply adequacy reached 94%, cumulative emissions fell to about 320,000 units, and cumulative profit rose to roughly 16,000 units. The overall sustainability score reached 85. Technology performs strongly because it simultaneously lowers resource intensity, reduces emissions, and strengthens reliability.

S6: Water shortage. Reduced water availability lowered supply adequacy to 65% and increased the final electricity shortage to about 1,820 units. Cumulative emissions declined to approximately 280,000 units, but this decrease was caused mainly by reduced generation and should not be interpreted as true environmental improvement. The resource dimension became the main bottleneck and the overall sustainability score was about 55.

S7: Fuel shortage. Fuel scarcity lowered supply adequacy to about 60%, final supply to around 3,150 units, and cumulative profit to roughly 1,800 units. Economic, technical, and resource scores fell sharply, and the overall sustainability score reached about 44. The result demonstrates that security of fuel supply is a prerequisite for sustainable thermal generation.

S8: Integrated policy. The integrated strategy combined controlled demand growth, technology upgrading, preventive maintenance, balanced carbon pricing, technology subsidies, and adequate water and fuel supply. Supply adequacy reached 96%, average efficiency 56%, and availability 96%. Cumulative profit increased to approximately 17,500 units and cumulative emissions fell to about 295,000 units. The overall sustainability score reached 91, the highest among all scenarios.

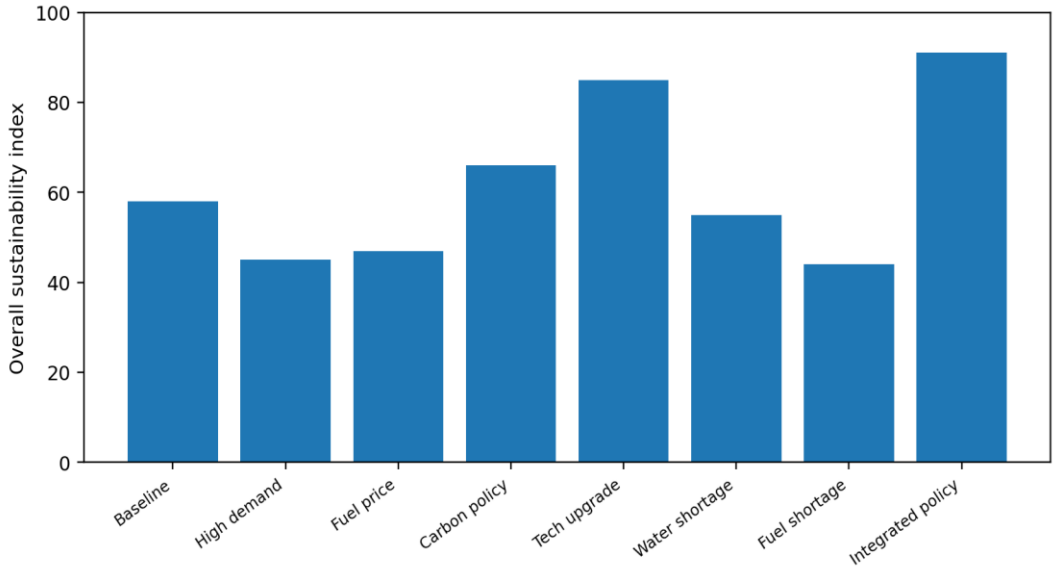
Table 11

Comparative scenario results.

Scenario	Supply adequacy	Cumulative profit	Cumulative emissions	Overall sustainability
S1 Baseline	88%	12,000	440,000	58
S2 High demand	72%	10,500	480,000	45
S3 Fuel price	86%	3,200	446,000	47
S4 Carbon policy	—	7,500	390,000	66
S5 Technology upgrade	94%	16,000	320,000	85
S6 Water shortage	65%	—	280,000	55
S7 Fuel shortage	60%	1,800	—	44
S8 Integrated policy	96%	17,500	295,000	91

Figure 6

Overall sustainability index across the eight agent-based scenarios.



Scenario comparison confirms that no single variable guarantees sustainability. Three major feedback loops were identified. First, the demand–generation–resource loop is reinforcing in an unfavorable direction: higher demand increases generation pressure, higher generation accelerates water and fuel consumption, and lower resource stocks subsequently reduce effective capacity. Second, the aging–failure–shortage loop links equipment aging and failure to lower availability and higher unmet demand, which can intensify operational pressure on the remaining healthy units. Third, the technology–efficiency–profit loop is reinforcing in a favorable direction: improved technology raises efficiency, reduces fuel use and emissions, and releases economic capacity that can support further investment.

The results also demonstrate the presence of bottlenecks. Increasing nominal capacity without secure resources cannot guarantee higher sustainable output. Similarly, imposing emission restrictions without allowing investment in cleaner and more efficient technology may improve environmental indicators while weakening economic viability. The integrated scenario performs best precisely because it avoids these one-dimensional interventions.

Behavioral validation was conducted through extreme-condition tests. When demand approaches zero, generation, resource use, and emissions are expected to approach zero. When fuel becomes unavailable, production should stop and unmet demand should approach total demand. A zero-water condition should constrain or stop production under the current cooling assumption. Higher efficiency should reduce specific fuel use and emissions. Removing carbon taxation should reduce policy cost and increase profit. Activating preventive maintenance should reduce failure frequency and variability in availability. The model displayed behavior consistent with these expectations.

Table 12

Extreme-condition validation of the ABM.

Test	Expected behavior	Assessment
Zero demand	Generation, resource use, and emissions approach zero	Logically confirmed
Zero fuel	Generation stops; unmet demand approaches total demand	Logically confirmed
Zero water	Generation is constrained or stopped	Logically confirmed
Higher efficiency	Fuel intensity and emissions decline	Logically confirmed
Zero carbon tax	Policy cost declines and profit increases	Logically confirmed
Preventive maintenance active	Failure rate and availability variability decline	Logically confirmed

4. Discussion and Conclusion

The present study developed an agent-based sustainability model for Iran's power-generation industry and demonstrated that power-plant sustainability is not determined by a single technical, economic, environmental, or policy variable but emerges from dynamic interactions among multiple dimensions. The qualitative phase identified six principal dimensions—technical and operational, environmental, economic, resource, institutional-policy, and social-human sustainability—and the simulation results further demonstrated that these dimensions are interconnected through reinforcing and balancing feedback loops. Technical and operational sustainability received the highest expert emphasis, while resource availability and policy coordination emerged as critical bottlenecks capable of restricting the performance of the entire system. This finding supports the broader argument that sustainable energy systems must be evaluated as integrated socio-technical systems rather than through isolated performance criteria. Previous research on energy transition similarly emphasizes that generation technology, infrastructure, resource availability, regulatory mechanisms, and system flexibility must be coordinated if sustainability improvements are to persist over time (Beck, 2025; Gitelman et al., 2023).

One of the most important findings was the central role of technical efficiency in linking several sustainability dimensions. In the model, lower efficiency increased fuel consumption per unit of generated electricity, which subsequently increased emissions, production costs, carbon-related liabilities, and pressure on fuel resources. Conversely, technological upgrading improved mean efficiency and equipment availability, reduced emissions, strengthened supply adequacy, and increased cumulative profit. The technology-upgrade scenario achieved an overall sustainability score of 85, substantially higher than the baseline score of 58. This multidimensional effect is consistent with research showing that technological innovation can simultaneously improve energy efficiency, environmental performance, resource productivity, and the long-term competitiveness of energy systems. Developments in materials engineering, for instance, have been identified as important enablers of the green transformation of the energy sector because improved materials can increase equipment efficiency and durability while reducing energy and material intensity (Yutong, 2025). Likewise, advances in wind-power technologies have focused on improving conversion efficiency, reliability, control, and grid compatibility, all of which contribute to more sustainable system-level performance (Elkelawy et al., 2025).

The findings also indicated that technological improvement is most effective when it is embedded within an integrated policy framework rather than implemented as an isolated intervention. The integrated-policy scenario, which combined technology upgrading, preventive maintenance, controlled demand growth, balanced environmental regulation, technology support, and improved fuel and water security, produced the highest overall sustainability score of 91. Supply adequacy reached 96%, average efficiency increased to 56%, equipment availability reached 96%, cumulative profit rose to approximately 17,500 units, and cumulative emissions declined to around 295,000 units. This result confirms that sustainability cannot be achieved through a single intervention because improvement in one subsystem may be neutralized by constraints elsewhere. The literature on sustainable energy transitions supports this interpretation. Diversification has been identified as an important mechanism for improving the sustainability and resilience of energy supply because it reduces dependence on individual technologies or fuels and provides greater flexibility under changing conditions (Gitelman et al., 2023). Similarly, analyses of national energy transitions demonstrate that system sustainability requires coordinated development of generation, infrastructure, flexibility mechanisms, policy incentives, and market structures rather than simple substitution of one generation technology for another (Beck, 2025).

Another significant result concerned the interaction between demand growth and supply adequacy. Under baseline conditions, electricity demand increased continuously while effective supply became increasingly constrained by unit capacity, failures, fuel depletion, and water availability. In the reconstructed baseline simulation, average demand reached approximately 8,172.38 units compared with average supply of only 2,800.03 units, resulting in average supply adequacy of 34.78%. In the scenario analysis, increasing demand growth from 3% to 6% reduced final supply adequacy from 88% under the baseline scenario to 72% and reduced the overall sustainability score to 45. These findings demonstrate that demand growth cannot be sustainably addressed by simply requiring existing generating units to produce more electricity. Sustainable responses must include efficiency improvement, demand-

side management, technological modernization, storage, distributed generation, and resource planning. Research on virtual power plants supports this conclusion by showing that coordinated renewable generation, energy storage, and demand-response mechanisms can strengthen grid flexibility and improve the ability of electricity systems to accommodate variable demand and generation (Liu et al., 2023). Similarly, two-stage energy-management strategies for wind–photovoltaic–hydrogen–storage microgrids demonstrate that dynamic coordination among generation, storage, and consumption can improve system performance under changing operating conditions (Wang, 2022).

Fuel security emerged as another major sustainability constraint. In the reconstructed baseline run, the initial fuel stock was completely depleted, while the fuel-shortage scenario reduced supply adequacy to approximately 60%, final electricity supply to around 3,150 units, cumulative profit to approximately 1,800 units, and overall sustainability to 44. These results indicate that thermal power generation remains highly vulnerable to fuel availability even when nominal generation capacity is sufficient. The findings are consistent with previous studies emphasizing the importance of diversification and secure energy inputs during energy transitions (Gitelman et al., 2023). They also support strategic research on renewable-energy development in Iran, which has emphasized the importance of reducing excessive dependence on fossil fuels and creating a more diversified and sustainable energy portfolio (Zahedi et al., 2022). In this respect, hybrid generation configurations may provide an intermediate pathway. Integrated solar and natural-gas combined-cycle systems can exploit renewable energy while maintaining dispatchable generation capacity, thereby potentially reducing fossil-fuel consumption without immediately sacrificing supply reliability (Alfaris et al., 2025).

Water availability was also shown to function as an important resource bottleneck. Under the water-shortage scenario, supply adequacy declined to 65%, and the electricity shortage increased to approximately 1,820 units. Although cumulative emissions also declined, this reduction was caused primarily by lower electricity generation rather than genuine improvements in environmental efficiency. This distinction is important because reductions in total emissions may provide a misleading indication of sustainability when they result from production constraints. The finding reinforces the importance of interpreting environmental performance jointly with generation output, efficiency, and resource availability. Sustainable infrastructure planning therefore requires models that capture resource constraints rather than focusing on emissions alone. Similar principles appear in sustainable network design research, where environmental improvement must be evaluated alongside operational capacity, resilience, congestion, and uncertainty (Babaei et al., 2022). The same logic applies to other resource-dependent systems in which apparent environmental gains can conceal deterioration in service provision or system resilience.

Environmental regulation produced another important trade-off. A stricter carbon-policy scenario reduced cumulative emissions from approximately 440,000 to 390,000 units and increased the environmental sustainability score, but cumulative profit declined to approximately 7,500 units. These findings indicate that carbon taxation and emission penalties can generate desirable environmental incentives but may simultaneously weaken economic sustainability if firms lack access to modernization technologies, financial support, or alternative energy inputs. This result supports the need for coordinated environmental policy rather than exclusive reliance on punitive instruments. Research on offshore sustainable-energy development likewise emphasizes that carbon-neutrality objectives may require combinations of clean-energy technologies and carbon-management mechanisms such as carbon capture, utilization, and storage (Xie, 2025). Moreover, the broader development of renewable electricity can create new opportunities for low-carbon industrial processes, as illustrated by research on sustainable single-cell protein production powered by variable renewable electricity (Fasihi et al., 2025). These studies indicate that environmental regulation becomes more effective when accompanied by technological pathways that enable firms to respond constructively rather than simply absorb additional costs.

The simulation also demonstrated the economic consequences of technical and resource deterioration. In the reconstructed baseline conditions, system profit declined from approximately 18,947.15 units in the first period to 5,571.29 units at model termination, while the cost-to-revenue ratio reached 90.58%. This decline resulted from the combined effects of constrained generation, fuel and environmental costs, equipment failures, and resource depletion. Therefore, economic sustainability cannot be interpreted independently from operational reliability and technological efficiency. Comparable relationships have been identified in sustainable supply-chain research, where resilience, environmental objectives, operating costs, and

uncertainty jointly influence system performance. Hybrid optimization of sustainable and resilient supply chains shows that systems designed solely for cost efficiency may become vulnerable when environmental pressures and disruption risks are ignored (Abbasian et al., 2023). Similarly, sustainable two-echelon network design demonstrates that congestion and uncertainty can alter economically optimal decisions and should be integrated into long-term planning (Babaei et al., 2022). The present findings extend this reasoning to electricity generation by showing that economic performance emerges from technical, environmental, and resource conditions rather than from pricing variables alone.

Equipment aging, stochastic failure, and maintenance also played central roles in the model. Aging increased failure probability, which reduced unit availability and electricity supply while increasing pressure on remaining operational units. Preventive maintenance operated as a balancing mechanism because it reduced failure frequency and improved system availability. The extreme-condition validation further confirmed that preventive maintenance reduced failure-related variability. These findings suggest that sustainability policy in aging thermal-generation systems should treat maintenance and reliability management as strategic sustainability instruments rather than routine operational activities. This perspective is consistent with the broader sustainable infrastructure literature, where digital tools and integrated modeling approaches are increasingly used to improve lifecycle decision-making. BIM-based sustainable structural optimization, for example, demonstrates how digital information environments can integrate performance, resource, and sustainability criteria across infrastructure life cycles (Afzal et al., 2023). Similar principles may be applied to power plants through predictive maintenance, digital twins, condition monitoring, and asset-management systems.

The findings additionally support the methodological suitability of agent-based modeling for power-generation sustainability. The model represented heterogeneous power plants with different capacities, efficiencies, ages, technology levels, and failure probabilities, together with a regulator and an electricity-demand agent. This allowed macro-level sustainability outcomes to emerge from micro-level interactions rather than being imposed through aggregate equations alone. Systematic reviews of agent-based methods in multi-energy systems have similarly concluded that ABM is especially useful when heterogeneity, adaptation, decentralized decisions, and policy interactions influence system outcomes (Yao et al., 2023). Agent-based research on organizational green-development behavior also shows that sustainability outcomes depend on interactions between firms, policies, organizational characteristics, and external pressures (Li et al., 2022). The present model applies this principle directly to power generation by allowing technical units, policy instruments, and demand dynamics to interact over time.

The use of ABM also makes it possible to represent nonlinear feedback and threshold behavior that conventional static approaches may overlook. For example, resource stocks may appear adequate during early simulation periods but become binding constraints after cumulative consumption crosses a critical threshold. Similarly, a small increase in failure probability may have limited effects when spare capacity exists but can cause severe shortages when demand is high. The ability to model these emergent patterns is one of the principal advantages of agent-based approaches. Computational advances in parallel ABM further increase the potential to expand models toward larger populations, more detailed agent structures, and more computationally intensive scenario analysis (Wang et al., 2022). As power-system models incorporate increasing numbers of generating units, consumers, storage systems, policies, and renewable technologies, computational scalability will become increasingly important.

The results also have implications for the transition toward more diversified and low-carbon generation technologies. Hydrogen-based fuel-cell systems, for example, have attracted attention because they may reduce emissions in sectors where conventional fossil-fuel technologies remain dominant. Reviews of hydrogen-fueled PEM fuel-cell applications demonstrate both substantial sustainability potential and continuing technological, infrastructure, and cost challenges (Dall'Armi et al., 2023). Similarly, offshore renewable-energy development, advanced wind systems, and integrated solar–gas technologies provide alternative pathways for reducing carbon intensity while preserving energy reliability (Alfaris et al., 2025; Elkelawy et al., 2025; Xie, 2025). Incorporating such technologies into future versions of the present model could provide a more comprehensive representation of Iran's energy-transition options and permit direct comparison of conventional thermal generation with hybrid, renewable, storage, and hydrogen-based alternatives.

A further implication concerns lifecycle sustainability and the circular economy. Energy-system transformation

generates new material flows and end-of-life challenges, particularly as batteries, storage systems, photovoltaic equipment, and other clean-energy technologies are deployed at larger scales. Research on retired electric-vehicle battery recycling demonstrates that sustainable energy transitions require dynamic reverse-logistics systems capable of balancing environmental impacts, costs, recovery rates, and network design (Mu et al., 2023). Thus, future sustainability models should not evaluate generation technologies solely during their operational phase but should progressively incorporate lifecycle resource requirements, material recovery, equipment replacement, and waste-management consequences. Such extensions would provide a broader understanding of whether apparent operational improvements remain sustainable when upstream and downstream impacts are considered.

Finally, the findings reinforce the importance of context-specific energy policy for Iran. Renewable-energy strategy research has indicated that Iran possesses significant renewable-energy potential but continues to face barriers associated with institutional arrangements, investment, policy implementation, and dependence on conventional energy resources (Zahedi et al., 2022). Spatial planning studies additionally show that energy infrastructure decisions should consider energy demand, environmental suitability, technical constraints, and long-term sustainability simultaneously (Akar et al., 2023). The present findings therefore suggest that Iranian power-sector policy should move beyond isolated interventions toward coordinated packages that combine technological modernization, reliability improvement, demand management, resource security, renewable diversification, and balanced environmental regulation. The superior performance of the integrated scenario provides empirical support for this approach and demonstrates that sustainability is maximized when technical, economic, environmental, resource, and institutional objectives are addressed together.

This study has several limitations that should be considered when interpreting its findings. First, detailed plant-level operational, financial, maintenance, failure, fuel-supply, and environmental data were not fully available, and some model parameters therefore relied on documented assumptions and expert judgments. Second, the empirical context was centered on Shahid Montazer Ghaem Power Plant and the broader conditions of Iran's thermal power-generation industry, which limits direct generalization to other power plants, generation technologies, or national electricity systems without recalibration. Third, some operational relationships were intentionally simplified to maintain computational transparency; for example, water consumption was modeled as directly proportional to generation, while fuel and emission relationships were represented through simplified coefficients. Fourth, the current computational model represents social and human sustainability largely indirectly through variables such as supply reliability, technology adoption, and maintenance performance rather than through explicit employee, household, community, or investor agents. Fifth, stochastic equipment failures introduce run-to-run variation, meaning that scenario results should be interpreted as simulation-based evidence rather than deterministic forecasts. Finally, the model focuses primarily on generation-side sustainability and does not fully represent transmission constraints, electricity-market mechanisms, renewable intermittency, detailed storage behavior, or cross-border electricity exchanges.

Future studies should extend the model through calibration with detailed unit-level operational data from multiple thermal, combined-cycle, hydroelectric, solar, and wind power plants so that cross-technology and cross-regional comparisons can be conducted. Replication across multiple generating facilities would permit external validation of the model and identify whether the sustainability relationships detected in the present study remain stable under different technical and climatic conditions. Future models should also incorporate explicit employee, consumer, investor, and local-community agents to represent social acceptance, workforce skills, safety behavior, demand response, and investment decisions. Additional research could integrate energy-storage systems, renewable intermittency, hydrogen production, carbon-capture technologies, transmission constraints, dynamic electricity pricing, fuel substitution, and detailed water-recycling mechanisms. Methodologically, combining agent-based modeling with system dynamics, mathematical optimization, machine learning, reinforcement learning, digital twins, and explainable artificial intelligence could improve forecasting and adaptive decision support. Monte Carlo analysis and extensive sensitivity testing should also be used to quantify uncertainty in failure probabilities, demand growth, resource availability, fuel prices, and regulatory parameters. Finally, future studies could incorporate lifecycle assessment and circular-economy mechanisms, including equipment replacement, battery recycling, material recovery, and decommissioning, to

provide a more comprehensive representation of sustainability across the full energy-technology lifecycle.

For practice, power-plant managers and policymakers should adopt integrated sustainability management rather than evaluating technical reliability, cost, emissions, and resource consumption separately. Priority should be given to improving generating-unit efficiency, implementing preventive and predictive maintenance, modernizing aging equipment, installing intelligent condition-monitoring systems, and establishing digital plant-management platforms capable of continuously tracking efficiency, failures, fuel use, water consumption, emissions, costs, and supply adequacy. Fuel-security strategies should include diversification of supply sources, improved fuel-storage planning, and greater integration of renewable and hybrid generation options. Water management should include recycling technologies, cooling-system optimization, leakage control, and continuous monitoring of water intensity per unit of electricity generated. Environmental policies should combine carbon pricing and emission limits with financial and technological support for modernization so that environmental improvement does not undermine economic viability. Demand-side management should be strengthened through load management, dynamic pricing, efficiency programs, and coordination with major electricity consumers. At the national level, an integrated power-generation sustainability database should be established to support benchmarking, scenario simulation, and evidence-based policy design. Before major regulatory or investment decisions are implemented, alternative policy packages should be tested through simulation so that unintended economic, technical, environmental, and resource consequences can be identified in advance.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

Acknowledgments

We would like to express our gratitude to all individuals helped us to do the project.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

References

Abbasian, M., Sazvar, Z., & Mohammadisiahroudi, M. (2023). A hybrid optimization method to design a sustainable resilient supply chain in a perishable food industry. *Environmental Science and Pollution Research*, *30*(3), 6080-6103. https://doi.org/10.1007/s11356-022-22115-8

Afzal, M., Li, R. Y. M., Ayyub, M. F., Shoaib, M., & Bilal, M. (2023). Towards BIM-based sustainable structural design optimization: A systematic review and industry perspective. *Sustainability*, *15*(20), 15117. https://doi.org/10.3390/su152015117

Akar, A. U., Uyan, M., & Yalpir, S. (2023). Spatial evaluation of the nuclear power plant installation based on energy demand for sustainable energy policy. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-023-03061-y

Alfaris, A., Akroot, A., Alqaed, S., & Almehmadi, F. A. (2025). Performance analysis of integrated solar and natural gas combined cycle power plants in high solar potential regions. *Scientific reports*, *15*(1). https://doi.org/10.1038/s41598-025-90377-6

Babaei, A., Khedmati, M., & Jokar, M. R. A. (2022). A branch and efficiency algorithm to design a sustainable two-echelon supply chain network considering traffic congestion and uncertainty. *Environmental Science and Pollution Research*, *30*(10), 28274-28304. https://doi.org/10.1007/s11356-022-24063-9

Beck, H. P. (2025). A comprehensive review of sustainable energy systems in the context of the German energy transition-part 1: Development status and system foundations. *Carbon Neutral Systems*, *1*(1). https://doi.org/10.1007/s44438-025-00012-0

Dall'Armi, C., Pivetta, D., & Taccani, R. (2023). Hybrid PEM fuel cell power plants fuelled by hydrogen for improving sustainability in shipping: State of the art and review on active projects. *Energies*, *16*(4). https://doi.org/10.3390/en16042022

Elkelawy, M., Bastawissi, H. A. E., & Seleem, H. E. (2025). Cutting-edge innovations in wind power: Enhancing efficiency, sustainability, and grid integration. *Pharos Engineering Science Journal*, *2*(1), 143-156. https://doi.org/10.21608/pesj.2025.369017.1020

Farfan Orozco, F. J. (2020). In-depth analysis of the global power infrastructure: Opportunities for sustainable evolution of the power sector.

Fasihi, M., Jouzi, F., Tervasmäki, P., Vainikka, P., & Breyer, C. (2025). Global potential of sustainable single-cell protein based on variable renewable electricity. *Nature Communications*, *16*(1). https://doi.org/10.1038/s41467-025-56364-1

Gitelman, L., Kozhevnikov, M., & Visotskaya, Y. (2023). Diversification as a method of ensuring the sustainability of energy supply within the energy transition. *Resources*, *12*(2), 19. https://doi.org/10.3390/resources12020019

Li, X., Li, J., Huang, Y., He, J., Liu, X., Dai, J., & Shen, Q. (2022). Construction enterprises' adoption of green development behaviors: An agent-based modeling approach. *Humanities and Social Sciences Communications*, *9*(1). https://doi.org/10.1057/s41599-022-01263-9

Liu, J., Hu, H., Yu, S. S., & Trinh, H. (2023). Virtual power plant with renewable energy sources and energy storage systems for sustainable power grid-formation, control techniques and demand response. *Energies*, *16*(9), 3705. https://doi.org/10.3390/en16093705

Mu, N., Wang, Y., Chen, Z. S., Xin, P., Deveci, M., & Pedrycz, W. (2023). Multi-objective combinatorial optimization analysis of the recycling of retired new energy electric vehicle power batteries in a sustainable dynamic reverse logistics network. *Environmental Science and Pollution Research*, *30*(16), 47580-47601. https://doi.org/10.1007/s11356-023-25573-w

Wang, J., Li, D., Lv, X., Meng, X., Zhang, J., Ma, T., Pei, W., & Xiao, H. (2022). Two-stage energy management strategies of sustainable wind-PV-hydrogen-storage microgrid based on receding horizon optimization. *Energies*, *15*(8), 2861. https://doi.org/10.3390/en15082861

Wang, K. (2022). Programmability and parallelization comparison of parallel agent-based modeling (ABM) libraries. University of Washington.

Xie, C. (2025). Research on sustainable offshore energy development in the context of carbon neutrality and carbon peaking, combined with CCUS. *Annals of Economics*, *1*(1), 60. https://doi.org/10.63313/Economics.2002

Yao, R., Hu, Y., & Varga, L. (2023). Applications of agent-based methods in multi-energy systems-A systematic literature review. *Energies*, *16*(5), 2456. https://doi.org/10.3390/en16052456

Yutong, M. (2025). Path analysis of materials engineering promoting green transformation of new energy industry based on sustainable development concept. *Journal of Technology Innovation and Engineering*, *1*(1), 11-19.

Zahedi, R., Zahedi, A., & Ahmadi, A. (2022). Strategic study for renewable energy policy, optimizations and sustainability in Iran. *Sustainability*, *14*(4), 2418. https://doi.org/10.3390/su14042418