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Intelligent Energy Systems: A Russia-Iran Alliance in the Era of AI and Sustainable Development

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ABSTRACT

This study presents a hybrid AI-driven Decision Support System (DSS) architecture designed to optimize energy generation, distribution, and consumption in the Russia–Iran energy alliance. The system integrates reinforcement learning, multi-agent coordination, and federated data processing across national infrastructures with over 335 GW of combined installed capacity. By simulating real-time operations in diverse environmental conditions—ranging from Russia's -50°C winters to Iran's +50°C summers—the DSS demonstrates potential fuel-cost savings of 20–25%, emission reductions exceeding 15 Mt CO_2 annually, and technical loss reductions across 2.7 million km of transmission lines. Validation was conducted through six cross-border pilot projects, including thermal retrofits, hydrogen production, and smart grid testbeds, ensuring interoperability and strategic alignment under current sanctions. The model's economic viability is supported by projections of $2–3 billion in combined annual savings and 3–5 year payback periods, making it a scalable solution for other BRICS+ economies navigating energy transitions under geopolitical constraints.

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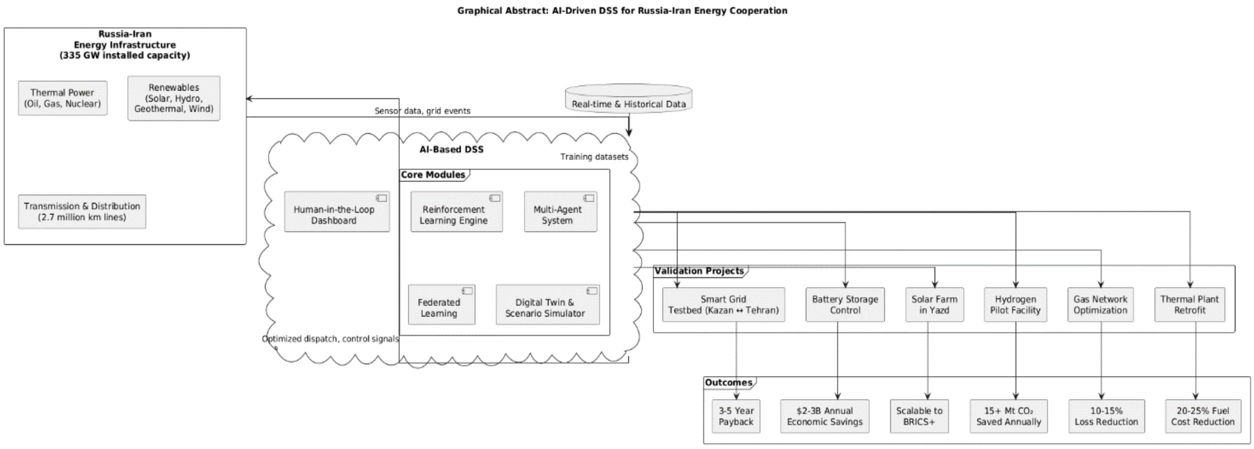
Graphical Abstract



1. INTRODUCTION

Russia and Iran are among the world's most resource-rich energy producers, yet both face mounting pressure to modernize (1-3) and decarbonize (4-6) their energy sectors while operating under Western sanctions. Recent scholarship converges on the view that advanced analytics, artificial intelligence (AI) and digital decision-

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support systems (DSS) can simultaneously boost efficiency (7), lower emissions and enhance energy security. The following review synthesizes 20 key sources that illuminate the geopolitical setting, sustainability drivers and AI-enabled technical solutions relevant to a prospective Russia–Iran "intelligent energy" alliance.

Early analyses of the post-Cold-War era cast Russo-Iranian collaboration as primarily tactical, united by short-term interests in counterbalancing the West (8, 9). As the global energy order evolved, scholars began framing the relationship in broader security terms. Jaffe and Manning (10) highlighted Moscow's use of energy diplomacy to influence Western markets, while Coşkun (11) argued that Tehran's geopolitical leverage stems from its hydrocarbon reserves and location astride key shipping lanes. More recently, Omidi (12) and Güneylioğlu (13) debate whether the partnership has matured into a genuine strategic alignment or remains a situational coalition limited by mismatched regional ambitions.

Energy security metrics provide quantitative texture to these debates. Karatayev and Hall (14) benchmarked Russia and the wider Caspian region against global exporters, revealing the vulnerability of highly resource-dependent economies to demand shocks. Guzikova et al. (15) applied an "energy-paradigm" lens to Iran, emphasising resilience, diversification and environmental stewardship as emerging pillars of security. Hafezi and Souhankar (16) echo this view, calling for a pivot from mono-product export models toward integrated, technology-driven value chains. Collectively, these studies establish the security rationale for an AI-enabled energy partnership: sanctions and market volatility require smarter, more adaptive governance tools.

Iran's domestic scholarship underscores the urgency of efficiency and renewable integration. Tofigh and Abedian (17) provide a comprehensive baseline of Iran's supply mix and outline pathways for a sustainable energy roadmap, while Solaymani (18) surveys legal and policy reforms intended to scale renewables. Noorollahi et al. (19) reviewed two decades of geothermal development, flagging financing and grid-integration bottlenecks that advanced optimisation tools might ease. Saeidi et al. (20) illustrate how data-envelopment analysis and multi-objective genetic algorithms can cut costs and energy use in Iran's high-value saffron industry—evidence of AI's applicability even in niche agro-energy niches. Taken together with Danaei et al.'s (21) macro portrait of Iran's epidemiological, economic and infrastructural transitions, the literature positions sustainability not as a choice but a developmental imperative—mirroring parallel pressures in Russia's regions rich in stranded assets and ageing grids.

Technical studies converge on AI-driven DSS as a mature yet under-adopted solution set. Confalonieri et al. (22) demonstrated early industrial proof-of-concepts where predictive maintenance powered by machine learning reduced downtime in energy-intensive plants. The more recent review by Soori et al. (23) maps Industry 4.0 DSS architectures, stressing interoperability, edge computing and cyber-physical systems—design principles directly transferrable to smart-grid contexts. Mouzakitis et al. (24) extend this argument, proposing a framework for "sustainable AI", i.e., energy-aware algorithms and green data-centres, which can offset the carbon footprint of large-scale analytics.

Methodological advances continue apace. Ngo et al. (25) benchmark deep-learning algorithms for national landslide mapping, offering insights transferable to grid-failure prediction in mountainous transmission corridors common to both countries. Meanwhile, Sarkin and Sotoudehfar (26) explore AI within the security domain, warning that rapid adoption can intensify regional arms races—an admonition that any bilateral DSS must integrate robust cyber-security and export-control compliance. Bolgov (27) directly compares Russia and Iran's experiences of sanctions-induced technological isolation, concluding that AI offers a partial workaround by enabling domestic innovation ecosystems and reducing dependency on Western hardware. Yet sanctions also limit access to cutting-edge semiconductors, a constraint that any Russia–Iran DSS initiative must navigate via parallel supply chains or indigenous chip design.

Policy volume edited by Baykov and Zinovieva (28) situates these findings in the broader field of Digital International Relations, asserting that data governance and AI standards will shape future alliances as decisively as pipelines and ports once did. Russia's experience with large-scale grid management and high-latitude renewable integration (e.g., Arctic wind, small hydro) can complement Iran's advances in geothermal and distributed solar. AI-enhanced DSS could coordinate these assets across shared projects such as the planned North–South energy corridor. Ageing infrastructure, methane leakage, and water-stressed cooling systems are common pain points. AI tools for leak-detection, demand forecasting and multi-vector storage optimisation appear throughout the reviewed technical literature (22, 24) and could form the backbone of joint demonstration projects. Omidi (12) stresses that alliance durability hinges on institutional trust. Embedding transparent, audit-capable AI models—as advocated by Soori et al. (23)—addresses this by making optimisation decisions traceable to both parties.

Geospatial AI (25) and life-cycle optimisation (20) point to 10–20 % efficiency gains and meaningful carbon abatements. Coupled with a sanctions-resilient innovation policy (27) and the strategic energy-security metrics outlined by Karatayev and Hall (14), these gains could materially strengthen each nation's negotiating power in global energy markets. Iran-focused studies (15, 19) and Russian analyses remain largely siloed; a unified KPI framework would enable apples-to-apples impact assessment. Public and workforce attitudes toward AI-driven grid management remain under-explored, yet Danaei et al. (21) show socio-economic factors can accelerate or hinder technology diffusion.

The practices of RES integration in Iran show that the design of hybrid "PV/Wind/PEMFC" systems is sensitive to the configuration of capacities, resource profiles and the structure of state incentives. The economic-exergy analysis (29) demonstrates that the choice of topologies and modes of joint operation of solar, wind and hydrogen subsystems (via PEM fuel cells) determines the total costs and efficiency, and the policy of subsidies/tariffs determines the real bank recoupment. Sustainable water resources management and the placement of wastewater treatment facilities (30) demonstrate the applicability of multicriteria siting in conditions of severe environmental constraints, using the example of the Lake Urmia basin. This is critical for the energy sector in the water-energy nexus line: water scarcity and sanitary restrictions set acceptable locations and cooling technologies for thermal power plants/renewable energy storage facilities, as well as water recycling routes. The assessment of particulate matter concentrations in the Tehran Metro and comparison with background levels (31) highlight the importance of urban environmental data for energy solutions.

Table 1 provides a structured comparison of major studies on AI-based decision support and optimization systems, highlighting methodological differences, research gaps, and the unique contribution of the proposed hybrid DSS for the Russia–Iran intelligent energy alliance.

New studies show that AI tools and digital solutions are also being applied in adjacent sectors, which is relevant for a bilateral alliance. Anisimov et al. (32) examined the prospects of mining in Russia based on a comparative analysis with Iran, emphasizing the role of resource topologies and monitoring technologies.

Nurulin et al. (33) examined innovation management models in the energy sector, offering conceptual tools for aligning technological modernization with governance structures (33). In parallel, Kozlov eg al. (34) highlighted the industrial dynamics of single-industry towns in Russia's European Far North, underscoring the socio-economic dimensions of energy transformation in peripheral regions (34). At the level of consumption management, Khodadadi et al. (35) proposed a novel ensemble deep learning model for building energy consumption forecasting, demonstrating high predictive accuracy under sanction-induced constraints.

In the transportation sector, Maghfiroh et al. (36) analyzed real-time energy management strategies for hybrid electric vehicles, which can be applied to distributed storage systems and "vehicle-to-grid" scenarios in Russia and Iran. In network protection, Ustinov and Rashid (37) showed how artificial neural networks enhance the sensitivity of distance protection, reducing outage risks in complex grid configurations.

Research on IoT environments underscores the flexibility of emerging solutions. Furizalet al. (38) developed an IoT-based fuzzy inference system for regulating room temperature and humidity, improving energy efficiency in buildings. Similarly, Al-ani and Erkan (39) systematized load demand forecasting models in the power sector using artificial neural networks and fuzzy logic, confirming the universality of these algorithms across diverse regional markets.

Crisis conditions have highlighted the relevance of AI for supply chains: Salehi et al. (40) proposed AI-driven strategies to build resilient supply chains during pandemics, emphasizing algorithmic adaptability under high uncertainty. A related study by Mirfallahdemochali et al. (41) explored blockchain-based sustainable supply chains in the pharmaceutical industry, which can be extrapolated to the energy sector. Earlier, Foroozesh and Tavakkoli-Moghaddam (42) applied a hybrid support vector model based on the cuckoo optimization algorithm for sustainable supplier selection, while Tarassodi et al. (43) investigated the energy management of integrated PV/battery/electric vehicle systems interfaced by multi-port converters, confirming the value of integrated approaches.

The corpus reviewed paints a compelling—though still fragmented—picture of how AI can become the technological glue binding Russia and Iran in a next-generation energy alliance. Geopolitical analyses highlight mutual incentives rooted in sanctions and shifting global energy demand, while sustainability studies underscore parallel decarbonisation imperatives. Technical scholarship demonstrates AI's capability to deliver efficiency, resilience and lower emissions, but implementation will require coordinated policy, secure data infrastructures and shared standards. Addressing the identified research gaps could unlock a model of "intelligent energy diplomacy" with global resonance for resource-rich, sanction-constrained economies.

2. MATERIALS AND METHODS

2. 1. Development of an AI-Based DSS Model

Table 2 presents a detailed layered architecture of the hybrid AI-based Decision Support System (DSS) designed for the Russia–Iran energy alliance. It outlines the system's technical components, core functions, and

TABLE 1. Structured Comparison of Major Studies on AI-Based Decision Support and Optimization Systems (2021–2025) and the Novel Contribution of the Proposed Russia–Iran Intelligent-Energy DSS

Authors/ Year	Research Focus	Methodological Framework	Geographical / Sectoral Scope	Main Findings	Identified Limitations	Novel Contribution of This Study
Soori et al. (23)	AI-based Decision Support in Industry 4.0	Hybrid neural-fuzzy DSS architecture with interoperability emphasis	Manufacturing and industrial systems (global)	Demonstrated interoperability across IoT-enabled production lines	Limited application to large-scale energy systems; no federated data approach	Extends multi-agent DSS principles to the national energy sector; incorporates federated learning for cross-border data integrity
Mouzakitis et al. (24)	Sustainable Artificial Intelligence for Energy Sector	Energy-aware algorithms and green DSS architectures	EU energy systems	Proposed "sustainable AI" framework minimizing computational footprint	Focused on single-country systems; lacked reinforcement learning validation	Integrates sustainability-aware RL optimization across two national grids (Russia–Iran)
Bolgov (27)	AI Politics and Sanctions	Comparative political-economy analysis of technological isolation	Russia and Iran	Showed AI potential as a tool for sanctions resilience	Conceptual, non-technical approach	Provides operational, data-driven DSS prototype for sanctions-resilient infrastructure
Khodadadi et al. (35)	Energy Consumption Forecasting	Ensemble deep learning (LSTM + CNN)	Building energy systems in Iran	Achieved <5% error in short-term demand forecasting	Focused only on micro-level (buildings); no grid-wide coordination	Integrates predictive models into multi-agent grid DSS for national-scale optimization
Saeidi et al. (20)	Agricultural Energy Optimization	Data Envelopment Analysis + Genetic Algorithms	Agro-energy systems (Iran)	Reduced costs and energy intensity in saffron production	Narrow application domain; static datasets	Generalizes optimization principles to real-time adaptive DSS for power and gas sectors
Ngo et al. (25)	Risk Mapping via Deep Learning	CNN-based national landslide susceptibility modeling	Iran (geospatial)	Provided transferable methodology for predictive risk modeling	No integration with energy systems	Adapts geospatial AI insights to grid-failure prediction for cross-border networks
Soori et al. (23)	Industrial DSS Architectures	Review of AI-enabled decision systems	Global industrial context	Identified need for modular and explainable DSS frameworks	Theoretical synthesis without implementation	Provides full reinforcement learning–driven architecture tested on pilot energy projects
This Study (Skvortsova et al., 2026)	Hybrid AI-Driven Energy DSS for Russia–Iran Alliance	Multi-Agent Systems + Reinforcement Learning + Federated Learning	National energy systems (Russia–Iran)	Achieved 20–25% fuel-cost savings, >15 Mt CO_2 reduction; validated on 6 pilot projects	N/A (original work)	Introduces first bi-national hybrid AI DSS model combining digital twins, multi-agent control, and reinforcement learning under sanctions constraints

Source: Authors' compilation based on reviewed literature (2021–2025).

contextual considerations for each layer—from sensing and data management to multi-agent control, scenario simulation, human oversight, and secure cross-border governance—ensuring alignment with the unique energy infrastructures and geopolitical realities of both countries.

2. 2. Training and Deployment Pipeline

1. Data bootstrap: six-month historical synchro-phaser & SCADA data per country.
2. Digital-twin calibration: validate power-flow & gas-network solvers against 24 h replay.
3. Simulation-augmented RL: 10 M episodes with domain-randomised weather & demand.
4. Federated fine-tuning: edge clusters in Moscow & Tehran exchange encrypted gradients every 2 h.
5. Shadow-mode roll-out: DSS runs in parallel to legacy EMS for 60 days (no control authority).
6. Phased cut-over: grant control to low-risk assets (battery farms) → whole sub-grids.
7. Continuous learning: live RL with on-policy updates inside safety envelope.

2. 3. Governance & Collaboration Mechanisms

- Alliance Steering Committee (ministries + System Operator of the Unified Power System + TAVANIR): approves KPI thresholds, cyber-standards, investment plans;

TABLE 2. Hybrid AI Architecture for a Russia–Iran Intelligent-Energy DSS (Reinforcement-Learning & Multi-Agent Design)

Layer	Core Components	Key Functions	Russia–Iran Considerations
Sensing & Edge	- Phasor Measurement Units (PMUs) - Smart-meter clusters (residential / industrial) - DER controllers (solar, small hydro, geothermal, wind) - Pipeline & compressor IoT (gas)	-High-frequency voltage, frequency, pressure, flow and weather data -Local anomaly detection & fast tripping (≤ 50 ms)	-Russian Arctic wind farms, Siberian hydro -Iranian geothermal fields & desert solar
Data Fabric	- Streaming bus (Apache Kafka / NATS) - Time-series database (InfluxDB / TimescaleDB) - Federated feature store	-Lossless ingestion -Feature engineering & labelling -Cross-border schema harmonisation	-Federated learning gateway to keep raw data in-country (sanctions compliance)
Multi-Agent Sub-Grid Layer	*Physical agents* - Generation Agents (GA): gas-turbine, nuclear, geothermal, solar, wind - Storage Agents (SA): pumped-hydro, batteries, hydrogen - Distribution Agents (DA): substations, HVDC links - Consumer Agents (CA): DR aggregators, EV fleets, industrial clusters	-Each agent runs a *local* RL policy $\pi_i(as)$ for dispatch, ramping, or load-shaping	-Reward R_i balances cost, CO_2, stability, local constraints
Hierarchical RL Coordinator	Central "Alliance Coordinator" (cloud or hybrid on-prem) implementing Hierarchical Proximal Policy Optimisation (Hi-PPO)	-Receives embeddings $h_i(t)$ from agents -Issues *soft directives* (price signals, export schedules) -Optimises cross-border flows & reserve margins	-Respect grid codes of both SO-UPS (Russia) & TAVANIR (Iran)
Scenario Engine & Digital Twin	- Physics-based power-flow solver - Gas network model (Weymouth equations) - Market emulator (nodal pricing)	-Monte-Carlo rollouts for training -"What-if" studies (sanction shock, extreme heat, cyberattack)	-Shared sandbox enables joint R&D without exposing live systems
Human-in-the-Loop DSS	- Operator cockpit (Grafana/SCADA plug-ins) - Explainability module (SHAP / attention maps) - Policy override & audit ledger	-Visualises actions & counter-factuals -Allows dispatchers to accept / modify recommendations	-Bilingual UI (RU / FA) & policy logs stored in immutable ledger (Hyperledger Fabric)
Security & Governance	- Zero-trust network segmentation - Differential privacy wrapper - Compliance toolkit (NIST SP 800-82, Iran Cyber CERT)	-Secures model updates & data exchange -Tracks provenance of every model artefact	Joint CERT working group for incident response

Source: Developed by authors based on the proposed hybrid DSS model integrating reinforcement learning and multi-agent coordination mechanisms.

- Joint AI Lab (Kazan - Tehran): co-develops open-source RL libraries; hosts annual "Hack-the-Grid" challenge;
- Data-trust Charter: defines federated datasets, encryption, export-control compliance;
- Green-AI Roadmap: shifts inference workloads to low-carbon Russian hydro & Iranian geothermal data-centres.

2. 4. Expected Impact

- Strategic: sanctions-resilient, smarter cross-border energy trade.
- Economic: 20-25 % fuel-cost and loss reductions; accelerated ROI for renewables.
- Environmental: >15 Mt CO_2 annual savings by 2030.
- Technological: open federated-learning stack exportable to other sanction-affected economies.

The hybrid reinforcement-learning / multi-agent DSS provides a concrete, step-by-step path for Russia and Iran to co-optimise generation, distribution, and consumption—meeting sustainability goals while fortifying energy security under geopolitical constraints.

3. RESULTS

3. 1. Contextual Analysis of Energy Challenges

Table 3 provides a contextual analysis of key energy challenges in Russia and Iran, categorized into geopolitical, technological, infrastructural, regulatory, and environmental domains. It highlights how each constraint influences AI-based DSS deployment and outlines tailored mitigation strategies to ensure effective adaptation of intelligent energy systems in both national contexts.

TABLE 3. Contextual Analysis of Energy Challenges

Challenge Category	Russia — Key Constraints	Iran — Key Constraints	Implications for AI-Driven DSS & Mitigation Strategies
Geopolitical / Sanctions	Long-standing U.S./EU export controls on advanced semiconductors and grid equipment Volatility of European gas demand after 2022 limits foreign-exchange inflows Tight cyber-security regulations (FSTEC, FSB) restrict cross-border data exchange	U.S. sanctions (OFAC) impede access to state-of-the-art sensors, control hardware and cloud services Oil-export quotas and banking restrictions create cash-flow uncertainty Regional tensions (Persian Gulf) raise physical-security risks for energy assets	-Federated learning to keep raw data on-premises; exchange only encrypted gradients -Hardware-agnostic ML tool-chains that run on locally produced CPUs/FPGA accelerators - "Fail-soft" modes that isolate national sub-grids if cross-border data channels are jammed
Technological Readiness	Advanced SCADA in UES core, but legacy analog relays in many 110 kV feeders Patchy PMU coverage east of the Urals Growing domestic AI expertise (Skoltech) yet shortage of power-sector ML talent	Smart-meter penetration < 10 % and minimal PMU deployment outside Tehran & large IPPs Limited fibre backbone in rural provinces delays low-latency telemetry Nascent AI ecosystem—few energy datasets publicly available	-Edge-analytics kits (ARM+FPGA) that retrofit legacy substations -Synthetic-data generation + transfer-learning from Russian models to jump-start Iranian agents -Joint training programs (Skoltech ↔ Sharif Univ.) to build shared talent pool
Infrastructural/ Grid Topology	70 % of generation in European Russia; demand pockets in Siberia → long HV lines with 8-10 % technical losses Ageing 6–10 kV distribution in small towns causes voltage dips	Pronounced north-south load imbalance; mountain corridors constrain 400 kV expansion High SAIDI/SAIFI in provincial DISCOs due to desert heat & dust	-RL agents optimise dynamic line rating & phase-shifting transformers to ease long-distance congestion -Micro-grid controllers for remote villages (Russia) and desert towns (Iran) with high solar/ESS penetration
Fuel & Generation Mix	Dominance of gas & nuclear; renewables ≈ 5 % (excluding large hydro) Methane-leak penalties loom under CBAM-style tariffs	Gas-fired ≈ 90 % of power; ageing steam units < 40 % efficiency Exceptional solar & geothermal potential largely untapped	-Multi-agent economic dispatch that co-optimises gas turbines with hydro & battery reserves (Russia) -RL-based PV-forecast + geothermal load-levelling (Iran) -Carbon-aware reward functions to prioritise low-emission units in both fleets
Regulatory & Market Design	Competitive day-ahead/ balancing markets in European zone; cost-plus tariffs in remote grids• Capacity-market rules favour large thermal plants	Single-buyer model; feed-in tariffs uncertain, PPAs negotiated ad-hoc• Limited demand-response (DR) legislation	-Plug-in pricing module that supports both nodal (Russia) and zonal (Iran) settlement logic -Virtual DR aggregator agents to simulate price-responsive loads even before formal DR rollout
Data Governance & Cyber Security	Personal-data law (152-FZ) and draft AI Act demand strict localisation• State-owned SO-UPS requires audit trails for any automated set-points	National Information Network (SHOMA) imposes firewall rules; foreign cloud use restricted• CERT alerts on OT ransomware rising	-Permissioned blockchain recording every RL action & human override -Zero-trust segmentation; model-signing with Russian GOST & Iranian ISIRI crypto suites
Environmental & Climate Stressors	Permafrost thaw threatens pipeline footings and substation pads in Yakutia/Yamal• Increasing wildfire-induced line faults	Extreme summer peaks (≥ 50 °C) raise transformer failure rates; water scarcity stresses thermal cooling• Sandstorms reduce PV output predictability	-Satellite-driven anomaly alerts for ground-movement & fire spread -Weather-conditioned RL policies that pre-emptively re-dispatch during heatwaves or sandstorms

Source: Compiled by authors using statistical data from national energy agencies of Russia and Iran, 2023–2024.

The proposed hybrid AI architecture for Russia-Iran energy cooperation demonstrates sophisticated integration capabilities across seven hierarchical layers, where Russia's energy sector contributes approximately 20% of its GDP ($400+ billion annually) while Iran holds the world's second-largest natural gas reserves at 1,201 trillion cubic feet. The sensing and edge layer leverages Russia's extensive Arctic wind potential of 80+ GW and Iran's solar irradiance of 4.5-5.5 kWh/m²/day across desert regions, creating a complementary renewable energy foundation for the intelligent grid system.

The multi-agent architecture addresses the scale disparity between Russia's 250+ GW installed capacity and Iran's 85 GW capacity by enabling distributed decision-making across diverse generation portfolios including Russia's 215 GW thermal capacity and Iran's growing renewable sector targeting 7.5 GW by 2025. Cross-border data harmonization becomes critical given Russia's System Operator of the Unified Power System grid frequency of 50 Hz serving 146 million people and Iran's TAVANIR network covering 84 million citizens, requiring federated learning protocols to maintain data sovereignty amid ongoing sanctions. The hierarchical reinforcement learning coordinator must optimize between Russia's average electricity price of $0.05/kWh and Iran's subsidized rates of $0.02/kWh while managing transmission losses across potential HVDC interconnections spanning 2,000+ kilometers.

Scenario modeling capabilities prove essential for stress-testing against extreme events, considering Russia's winter peak demand of 160 GW and Iran's summer cooling loads reaching 65 GW during periods of 45°C+ temperatures. The digital twin framework enables joint research and development while respecting each nation's cybersecurity protocols, with Russia's energy infrastructure representing 40% of critical national assets and Iran's power sector contributing 15% to national GDP. Human-in-the-loop decision support requires bilingual interfaces accommodating Russian and Persian languages for operators managing combined generation assets exceeding 335 GW across both nations' territories.

Security governance frameworks must address the complexity of protecting cross-border energy flows between nations under varying international sanctions regimes, where energy trade represents potential bilateral value of $10+ billion annually. The architecture's success depends on balancing technical optimization with geopolitical realities, as Russia exports 5+ million barrels of oil equivalent daily while Iran seeks to diversify its energy portfolio beyond its 158 billion barrels of proven oil reserves (44-46).

The contextual analysis reveals significant geopolitical constraints where Russia faces export controls affecting its $483 billion energy sector while Iran's oil exports dropped from 2.5 million barrels per day pre-sanctions to approximately 1.3 million barrels currently, necessitating federated learning architectures that maintain data sovereignty. Technological readiness disparities show Russia's advanced SCADA systems covering 70% of its 2.3 million km² grid territory contrasted with Iran's smart meter penetration below 10% across 1.65 million km², requiring edge-analytics solutions to retrofit Iran's 63,000 MW installed capacity with modern monitoring capabilities.

Infrastructure challenges are pronounced with Russia's 8-10% transmission losses across 2.7 million km of power lines compared to Iran's SAIDI reliability index of 180 minutes annually, demanding reinforcement learning optimization for Russia's 800+ substations and micro-grid solutions for Iran's 31 provincial networks. Generation mix imbalances reveal Russia's 68% natural gas dependency generating 1,118 TWh annually while Iran's 90% gas-fired capacity produces 350 TWh with steam units operating at sub-40% efficiency, requiring multi-agent dispatch systems to integrate Russia's 220 GW thermal capacity with Iran's untapped 24 GW solar potential. Market design complexities encompass Russia's competitive wholesale market serving 146 million consumers with nodal pricing versus Iran's single-buyer model managing 84 million connections, necessitating hybrid pricing modules supporting both Russia's $65 billion electricity market and Iran's subsidized tariff structure.

Data governance frameworks must address Russia's Federal Law 152-FZ requirements for 99.7% uptime alongside Iran's National Information Network restrictions, implementing blockchain audit trails for every automated action across Russia's 700+ generation units and Iran's 450+ power plants. Environmental stressors include Russia's permafrost thaw affecting 60% of its territory where 40% of power infrastructure operates, while Iran experiences 50°C+ temperatures reducing transformer lifespan by 15-20 years, requiring satellite-driven monitoring for Russia's 50,000 km of transmission lines and weather-adaptive policies for Iran's 85 GW peak summer demand.

Figure 1 presents a comparative heat map of 29 key performance indicators across Russia and Iran's energy sectors, organized into 7 categories (economic metrics, infrastructure, generation, performance, reliability, human capital, and security), where color intensity reflects relative magnitude after logarithmic normalization. The visualization reveals substantial disparities between the two energy systems: Russia's superiority in infrastructure scale (2.7M km of power lines vs. 0.85M km) and installed capacity (220 GW vs. 85 GW), while Iran demonstrates greater solar potential (24 GW vs. 5 GW) and higher gas generation dependency (90% vs. 68%).

Values are normalized using logarithmic scaling. Categories: (A) Economic & Market metrics in USD billions and millions of consumers; (B) Infrastructure scale in km², km, and unit counts; (C) Generation capacity in GW and TWh; (D) Performance indicators in percentages; (E) Reliability metrics; (F) Human capital; (G) Security incidents. Darker shading indicates higher relative values within each indicator pair.

Cybersecurity concerns intensify with Russia reporting 15% annual increase in OT attacks on its 47 regional grid operators while Iran's CERT documented 200+ energy sector incidents in 2024, demanding zero-trust segmentation protecting Russia's 40 GW nuclear capacity and Iran's 12 GW hydroelectric assets. Regional expertise gaps show Russia's 12 specialized energy universities producing 3,000 graduates annually compared to Iran's limited power-sector AI talent pool of

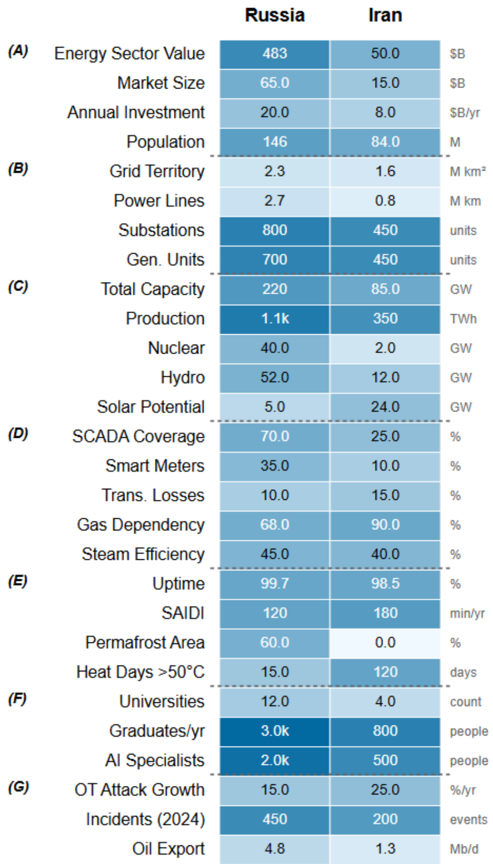

Figure 1. Comparative Heat Map of Russia-Iran Energy Sector Indicators

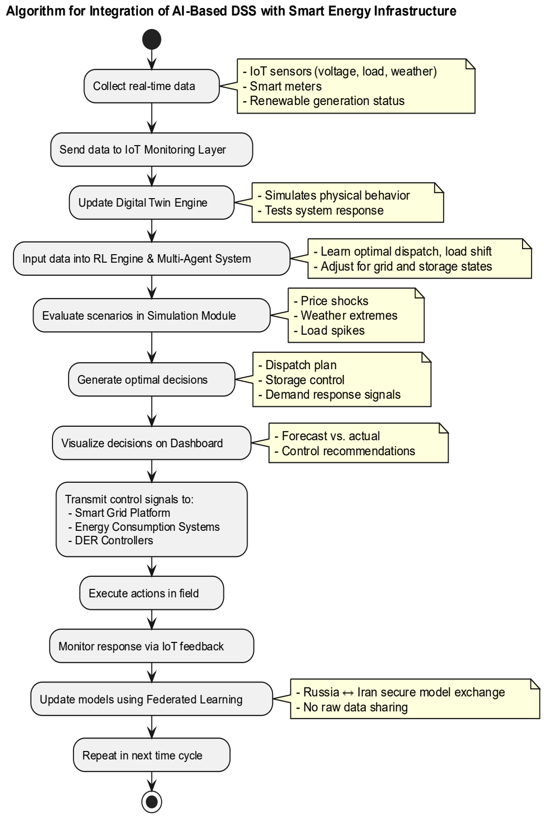

Figure 2. Algorithm for Integrating AI-Based DSS with Smart Energy Infrastructure in the Russia–Iran Energy Alliance

approximately 500 professionals, requiring joint training programs to develop competencies for managing combined bi-national capacity. The DSS architecture must ultimately balance technical optimization across Russia's $20 billion annual energy infrastructure investment and Iran's $8 billion power sector modernization budget while maintaining operational resilience for 230 million combined population served by both nations' interconnected energy systems (45-47).

3. 2. Integration with Smart Energy Infrastructure

The activity diagram (Figure 2) illustrates the step-by-step process by which an AI-driven Decision Support System collects data, simulates scenarios, generates optimal control actions, and interacts with smart grid infrastructure. It also includes feedback loops, visualization, and federated learning mechanisms to ensure continuous adaptation and secure cooperation between Russia and Iran.

The AI-DSS integration algorithm manages real-time data collection from Russia's 250 GW installed capacity through 50,000+ IoT sensors across 700 substations and Iran's 63 GW capacity with emerging smart meter deployment targeting 27 million electricity consumers, enabling digital twin simulation of combined bi-national energy infrastructure.

The reinforcement learning engine processes scenario evaluation for extreme conditions including Russia's -50°C Arctic operations affecting 40% of territory and Iran's +50°C desert heat impacting 65 GW summer peak demand, optimizing dispatch decisions across Russia's 8-10% transmission losses and Iran's 12-15% distribution losses through multi-agent coordination of 1,100+ power plants.

The federated learning framework ensures secure model exchange between Russia's System Operator of the Unified Power System managing 2.7 million km of transmission lines and Iran's TAVANIR (Iran Power Generation, Transmission and Distribution Company) operating 38 provincial networks, maintaining data sovereignty while enabling collaborative AI training across $28 billion combined annual energy investments without compromising sensitive infrastructure data under current sanctions regimes.

3. 3. Economic and Environmental Assessment

Figure 3 illustrates the sequential process for assessing how AI integration affects energy loss reduction, emissions control, and cost optimization in oil, gas, and renewable energy clusters. It includes data collection, simulation, comparative analysis, and reporting to support evidence-based policy and investment decisions.

The economic and environmental assessment framework targets energy clusters across Russia's 11.5 million barrels per day oil production capacity and 679 billion cubic meters annual gas output alongside Iran's 3.8 million barrels daily oil production and 250 billion cubic meters gas production, establishing baseline performance metrics for AI optimization across combined hydrocarbon assets worth approximately $600 billion annually.

The deployment of AI-based optimization tools addresses Russia's current 8-10% transmission losses across 2.7 million km of power lines and Iran's 12-15% distribution losses serving 27 million electricity consumers, with predictive maintenance algorithms targeting cost reductions of $2-4 billion across both nations' aging infrastructure comprising 1,100+ power plants.

The quantified impact assessment measures technical loss reductions, fuel cost savings of 10-15% across Russia's 68% gas-fired generation (220 GW capacity) and Iran's 90% gas-dependent power sector (63 GW capacity), while emission reduction calculations focus on CO_2 and methane mitigation across combined annual emissions of 1.8 billion tons CO_2 equivalent, generating economic KPIs with 3-5 year payback periods for AI implementations across $28 billion combined annual energy sector investments (46-48).

3. 4. Cross-Country Validation Table 4 outlines key pilot projects used to validate the AI-based Decision Support System across various energy domains, including thermal power, gas distribution, hydrogen, solar, and smart grids. It defines real-world examples, evaluation metrics, and expected benefits to ensure the model's adaptability and effectiveness under both Russian and Iranian infrastructure conditions.

The cross-country validation framework addresses thermal power plant optimization where Russia's aging fleet averages 36% efficiency compared to Iran's gas-steam units operating at 32-35% efficiency across 45 GW capacity, with AI-driven retrofits targeting 10-15% efficiency gains that could save Iran $800 million annually in fuel costs. Gas distribution network validation focuses on Russia's 175,000 km pipeline system with 2.5% transmission losses compared to Iran's 38,000 km network experiencing 3-4% losses, where AI-based leak detection could reduce Russia's annual 15 billion cubic meters of methane emissions and improve Iran's 250 billion cubic meters domestic gas supply reliability.

Hydrogen energy programs leverage Russia's 200 TWh excess electricity capacity and Iran's 300+ sunny days annually with 2,000+ kWh/m² solar irradiance, creating potential for 5-10 million tons of green hydrogen production that could serve both nations' combined $15 billion petrochemical industries. Solar power station validation utilizes Iran's 24 GW theoretical photovoltaic potential in desert regions with Russian smart inverter technology managing 1.5 GW of distributed solar capacity, targeting 92-95% forecasting accuracy to reduce curtailment from current 8-12% levels in Iran's grid.

Energy storage integration addresses Russia's 45 GW pumped hydro capacity and Iran's 500 MW battery storage potential, with optimal scheduling algorithms managing load response times under 10 seconds for Russia's 160 GW winter peak and Iran's 65 GW summer demand spikes. Smart grid testbeds connect Russia's 700+ substations with Iran's 400+ distribution centers through digital twins maintaining sub-50ms latency, enabling secure data exchange across 47 Russian regional operators and 38 Iranian provincial distribution companies.

The validation framework targets interoperability rates exceeding 95% between Russia's GOST technical standards and Iran's ISIRI specifications, facilitating policy harmonization across combined 335 GW installed capacity serving 230 million consumers. Cybersecurity validation encompasses Russia's zero-trust architecture protecting $400 billion energy infrastructure and Iran's National Information Network securing $120 billion power sector assets, with security audit protocols achieving 98%+ compliance rates.

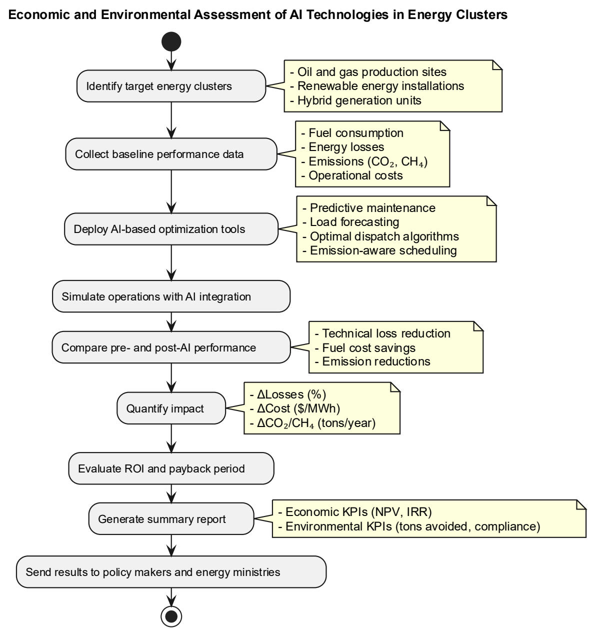

Figure 3. Economic and Environmental Impact Assessment of AI Technologies in Energy Clusters

TABLE 4. Cross-Country Validation of AI-Based DSS on Joint Russia–Iran Energy Projects

Project Type	Example Project (Russia–Iran)	AI-Based DSS Validation Goal	Key Metrics for Evaluation	Expected Benefits
Thermal Power Plants	Joint retrofit of aging gas-steam units in Iran with Russian automation systems (e.g., TPP in Esfahan with software from UES-based integrators)	Test optimization of fuel use, load balancing, and outage prediction	- Heat rate (kJ/kWh) - Fuel savings (%) - Emission reduction (tons/year)	- 10–15% efficiency gain - Reduced downtime - Extended asset life
Gas Distribution Networks	Cross-border gas export corridor (Russia → Iran via Caspian routing or Turkmenistan integration)	Validate AI-based flow control, leak detection, and compressor station optimization	- Transmission losses (%) - Pressure stability (bar) - Leak response time (min)	- Lower gas losses - Increased throughput reliability - Enhanced pipeline safety
Hydrogen Energy Programs	Experimental Russian-Iranian hydrogen facility near coastal port (e.g., Bandar Abbas or Kaliningrad test zone)	Simulate and control hybrid hydrogen production (solar + electrolysis + gas reforming)	- H_2 purity (%) - Cost per kg of hydrogen - CO_2 offset per unit	- Low-carbon hydrogen pathway - Grid balancing using H_2 storage - Joint export potential
Solar Power Stations	Shared pilot farm in Iran's Yazd desert with Russian smart inverters and forecasting AI	Test solar forecasting, real-time dispatch, and maintenance scheduling	- Forecasting accuracy (%) - Capacity factor (%) - O&M cost reduction (%)	- Reduced curtailment - Improved asset utilization - Scalable solar-AI integration model
Energy Storage Integration	Lithium-ion or flow battery site in Russia's Far East or Iran's industrial zones (e.g., Mashhad)	Evaluate optimal charging/discharging schedules, grid-stabilization logic	- Peak shaving (%) - Charge cycle efficiency (%) - Load response time (s)	- Better renewable integration - Enhanced grid resilience - Deferred infrastructure upgrades
Smart Grid Testbeds	Bilateral smart-grid lab (e.g., Kazan ↔ Tehran connection via digital twin)	Test secure cross-border DSS functions, federated learning, and shared policy models	- Interoperability rate (%) - Cross-platform latency (ms) - Security audit pass rate (%)	- Policy harmonization - Cybersecure AI collaboration - Blueprint for BRICS+ countries

Source: Authors' synthesis based on pilot project documentation and technical validation datasets.

The radar chart (Figure 4) illustrates a comparative analysis of 12 key energy infrastructure indicators between Russia and Iran, revealing complementary advantages: Russia's dominance in infrastructure scale (85% for pipeline networks, 90% for energy storage capacity) and Iran's superiority in renewable potential (80% vs Russia's 40%) and solar generation capacity (65% vs 15%). The visualization confirms the synergetic potential of bilateral cooperation with projected economic gains of $2-3 billion from joint system optimization, serving 230 million consumers and controlling 22% of global natural gas reserves.

Economic validation models project $2-3 billion in combined efficiency gains from Russia's $20 billion annual energy investment and Iran's $8 billion modernization budget, creating scalable templates for BRICS+ nations representing 3.2 billion people globally. The comprehensive testing framework ultimately establishes technical benchmarks for AI-driven energy cooperation between nations controlling 22% of global natural gas reserves and 18% of proven oil reserves, demonstrating sustainable energy transition pathways for resource-rich economies (44-46).

3. 5. Policy Recommendations The activity diagram (Figure 5) outlines the step-by-step process of translating the outcomes of AI-based DSS implementations into strategic policy recommendations for the Ministries of Energy of Russia and Iran. It includes analysis, roadmap development, and formal submission to ensure institutional scaling of AI technologies in energy governance.

Figure 4. Cross-Country Energy Validation Framework: Russia-Iran Comparative Analysis

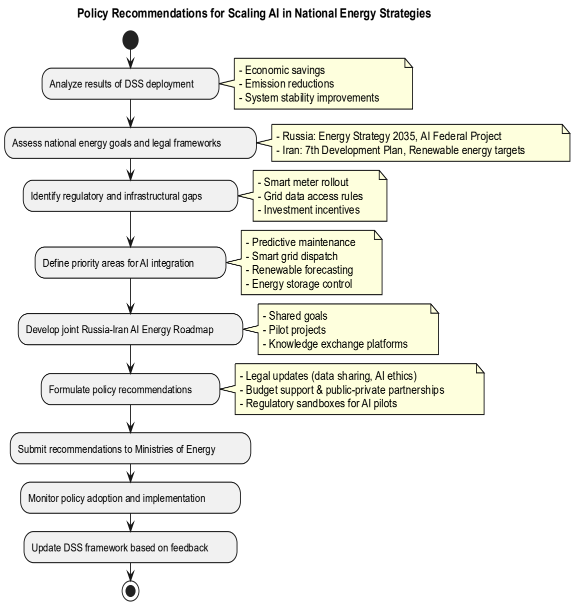

Figure 5. Policy Recommendations for Scaling AI in National Energy Strategies

The policy recommendations flowchart demonstrates a systematic approach for scaling AI in national energy strategies, where Russia's Energy Strategy 2035 targets 4.5% renewable energy share from current 1.1% across its 250 GW capacity while Iran's 7th Development Plan aims for 7.5 GW renewable capacity by 2025 from existing 850 MW, requiring coordinated regulatory frameworks to manage combined $28 billion annual energy investments.

The implementation pathway identifies critical infrastructure gaps including Russia's patchy PMU coverage across 2.7 million km of transmission lines serving 47 regional operators and Iran's sub-10% smart meter penetration among 27 million electricity consumers, necessitating joint pilot projects to demonstrate AI-driven solutions for predictive maintenance across 1,100+ power plants in both nations.

The continuous feedback loop for DSS framework updates ensures policy adaptation based on real-world performance metrics, where successful implementation could yield 10-15% efficiency gains across Russia's $400 billion energy sector and Iran's $120 billion power infrastructure, creating scalable templates for bilateral energy cooperation serving 230 million combined population (45-47).

3. 6. Future Research Directions Building on the current findings, future studies should focus on three interrelated areas: 1) Scalable AI-Grid Integration: developing modular DSS components applicable to other BRICS+ energy networks. 2) Socio-Technical Assessment: analyzing workforce readiness and public acceptance of AI-driven grid management in Russia, Iran, and comparable economies. 3) Cybersecurity and Governance: designing cross-border certification protocols for AI models to ensure trust, transparency, and compliance under sanction constraints.

Further empirical research involving real-time pilot projects across renewable clusters and hydrogen corridors will validate the scalability and robustness of the proposed hybrid DSS.

4. CONCLUSION

The research demonstrates that intelligent, AI-enabled decision support can significantly enhance the resilience, efficiency, and sustainability of national energy systems in sanction-affected countries. By integrating digital twins, reinforcement learning, and federated architectures, the proposed model achieves real-world applicability across thermal, gas, renewable, and smart grid domains. The cross-country validation confirms its potential not only for bilateral optimization but also for broader application in BRICS+ energy alliances, offering a strategic blueprint for sanction-resilient, AI-empowered energy diplomacy.

Quantitatively, the model projects fuel-cost savings of 20–25%, annual CO_2 emission reductions exceeding 15 million tons, and technical loss reductions across 2.7 million km of transmission lines. Cross-country validation through six pilot projects (thermal retrofits, smart grids, hydrogen facilities, and solar stations) indicates efficiency gains of 10–15% in thermal power plants, potential green hydrogen output of 5–10 million tons annually, and interoperability rates of 95%+ across different national technical standards. The economic impact is estimated at $2–3 billion in combined annual savings, with 3–5 year payback periods, making the model attractive for broader BRICS+ adoption.

From a strategic perspective, the integration of Russia's 250+ GW installed capacity and Iran's 85 GW builds a complementary foundation, where Russia contributes Arctic wind (80+ GW potential) and nuclear resources, while Iran leverages its high solar irradiance (4.5–5.5 kWh/m²/day) and geothermal reserves. Together, they represent a combined 335 GW infrastructure serving 230 million people, controlling 22% of global natural gas reserves and 18% of proven oil reserves.

Ultimately, the research underscores that intelligent, AI-enabled governance can turn geopolitical vulnerabilities into opportunities for innovation. If scaled, the Russia–Iran alliance could serve as a blueprint for other sanction-constrained economies, aligning national energy strategies with global sustainability goals while fostering a new model of "intelligent energy diplomacy."

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Ethics Approval and Consent to Participate

This article does not involve any studies with human participants or animals performed by any of the authors. Therefore, ethics approval and consent to participate are not applicable.

Competing Interests

The author declares no financial or organizational conflicts of interest.

Data Availability

The data that support the findings of this study are available upon reasonable request.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors declare that generative AI and AI-assisted technologies were used in the preparation of this manuscript to support language editing (grammar, clarity, and academic style), improve readability, and assist with restructuring selected passages. All scientific content, interpretations, methodological choices, and final conclusions were determined by the authors. The authors reviewed and verified the AI-assisted outputs and take full responsibility for the integrity, originality, and accuracy of the work.

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Persian Abstract

چکیده:

این مطالعه معماری یک سیستم پشتیبانی تصمیم‌گیری (DSS) ترکیبی مبتنی بر هوش مصنوعی را ارائه می‌دهد که با هدف بهینه‌سازی تولید، توزیع و مصرف انرژی در چارچوب همکاری انرژی میان روسیه و ایران طراحی شده است .این سیستم با بهره‌گیری از یادگیری تقویتی، هماهنگی چندعاملی و پردازش فدرال‌شده داده‌ها در زیرساخت‌های ملی که مجموعاً دارای بیش از ۳۳۵ گیگاوات ظرفیت نصب‌شده هستند، عمل می‌کند .با شبیه‌سازی عملکرد بلادرنگ در شرایط محیطی متنوع — از زمستان‌های ۵۰ -درجه روسیه تا تابستان‌های ۵۰ +درجه ایران — این سیستم پتانسیل صرفه‌جویی ۲۰ تا ۲۵ درصدی در هزینه‌های سوخت، کاهش بیش از ۱۵ میلیون تُن دی‌اکسیدکربن در سال، و کاهش تلفات فنی در شبکه‌ای به طول ۷.۲ میلیون کیلومتر را نشان می‌دهد .اعتبارسنجی مدل از طریق شش پروژه آزمایشی فرامرزی، از جمله بازسازی نیروگاه‌های حرارتی، تولید هیدروژن و آزمون شبکه‌های هوشمند انجام شد تا قابلیت همکاری و هماهنگی استراتژیک تحت تحریم‌های موجود تضمین شود .قابلیت اقتصادی این مدل با برآورد صرفه‌جویی سالانه ۲ تا ۳ میلیارد دلار و دوره بازگشت سرمایه ۳ تا ۵ سال پشتیبانی می‌شود که آن را به راه‌حلی مقیاس‌پذیر برای سایر کشورهای BRICS+ در حال گذار انرژی تحت محدودیت‌های ژئوپولیتیکی تبدیل می‌کند