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ORGINAL RESEARCH PAPER

Designing a Smart Model for Energy Imbalance Management in Iranian Industries Using Blockchain Technology Under Sanction Constraints

Seyyed Abdollah Razavi [a, *]; Saeeid Saniei [b]

[a] *Department of Petroleum Economics and Energy Diplomacy, Tehran Faculty of Petroleum, Petroleum University of Technology (PUT), Abadan, Iran.*
[b] *Department of Management, Faculty of Management, Industrial Management, Islamic Azad University, Electronic Campus, Tehran, Iran.*

**. Corresponding Author's Email: Srazavi@put.ac.ir*

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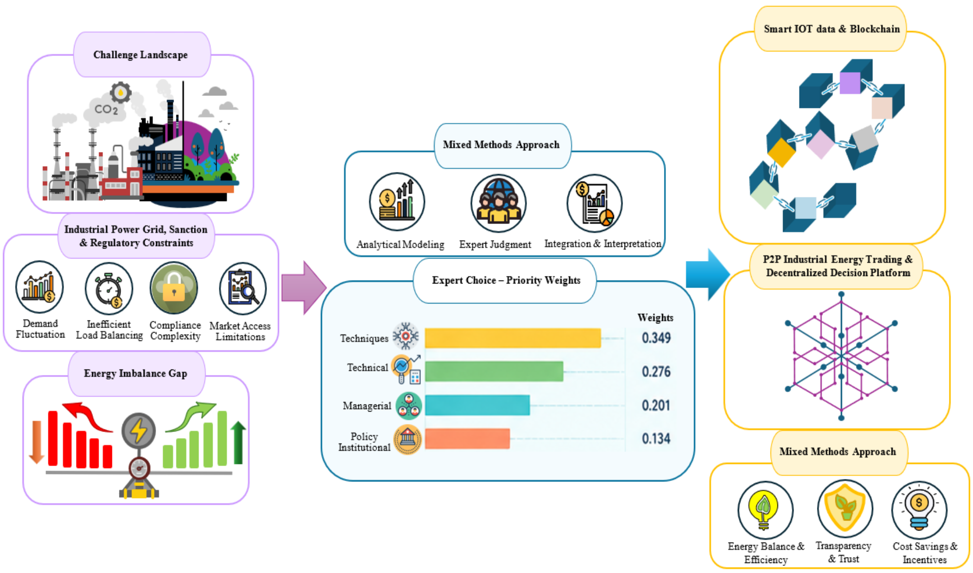
A B S T R A C T

In recent years, energy imbalance has emerged as one of the fundamental challenges facing Iran's energy system, particularly within the industrial sector. Rising demand, inefficient consumption patterns, infrastructural constraints, and the ramifications of economic sanctions have severely complicated the management of energy supply and demand. This study aims to design a smart model for energy imbalance management in Iranian industries based on blockchain technology, utilizing an applied mixed-methods approach. In the qualitative phase, the effective dimensions and indicators were identified through a literature review and semi-structured interviews with energy and industry experts. In the quantitative phase, the prioritization of these factors was determined using the Analytic Hierarchy Process (AHP) implemented in Expert Choice software (version 11). The findings revealed four primary dimensions: Blockchain-based Technological, Technical, Managerial, and Policy-Institutional, with the Technological dimension ranking first with a weight of 0.349. The proposed model was designed across three layers: Data Collection and Consumption Measurement, Blockchain and Smart Contracts, and Smart Services and Decision-Making. By enabling transparent and immutable data recording, creating decentralized markets, facilitating peer-to-peer energy trading, and providing smart quota allocation, this model offers a localized and actionable framework for managing energy imbalance under Iran's institutional and sanction-constrained conditions.



1. Introduction

Energy, as one of the most critical inputs of production, plays a foundational role in the sustainability, competitiveness, and productivity of industries. In industrial economies, sustainable, reliable, and cost-effective access to energy carriers such as electricity, natural gas, and liquid fuels is considered a prerequisite for continuous production and industrial growth (Heydari, 2024; Maurits et al., 2025). Nonetheless, in recent years, Iranian industries have confronted a structural and escalating phenomenon known as energy imbalance—a state characterized by a chronic mismatch between energy supply and demand across various time intervals, the adverse impacts of which are directly manifested in the industrial sector (Safaei et al., 2025).

Energy imbalance in Iran has emerged concurrently across multiple primary energy carriers. In the electricity sector, the growth of industrial consumption, deteriorating infrastructure, and investment deficits have resulted in both scheduled and unforced power outages (Juybari et al., 2025). In the natural gas sector, particularly during cold seasons, prioritizing residential consumption leads to supply curtailments or outright shutdowns for industrial consumers. Similarly, in the realm of liquid fuels, supply and logistics fluctuations have confronted industries with severe operational uncertainty. This situation underscores a chronic and structural imbalance within the country's energy management governance, rather than merely an episodic or purely technical disruption (Bagheri Moghaddam et al., 2024).

The ramifications of energy imbalance on Iranian industries are multifaceted and profound. First, industrial productivity declines significantly due to the shutdown of production lines, underutilization of operational capacities, and increased material waste. Energy interruptions prevent industrial plants from operating at their nominal capacities, driving up unit manufacturing costs. Second, production security is severely threatened; uncertainty regarding a reliable energy supply exposes production planning, contractual fulfillment, and supply chain continuity to extreme risks. Third, energy imbalances generate substantial hidden energy costs—such as premature equipment depreciation, recourse to expensive alternative sources, increased burning of polluting fuels, and workforce idle time. Although frequently omitted from formal corporate accounting records, these hidden costs exert a detrimental toll on industrial profitability (Faryadras, 2025).

These systemic challenges have been further exacerbated by international sanction constraints. Economic sanctions have systematically curtailed effective access to global energy markets, modern energy management technologies, and foreign financial resources. Furthermore, restrictions on technological and data transfers have hindered the deployment of smart, integrated, and transparent energy management platforms across industries, thereby entrenching reliance on legacy, fragmented, and siloed approaches. Under such conditions, information opacity and a pervasive deficit of trust among stakeholders across the energy value chain (the state, industries, energy utilities, and regulatory bodies) have intensified systemic inefficiency (Omokara et al., 2025; Moabi et al., 2024).

Consequently, the adoption of emerging technologies to transcend this status quo represents an indispensable necessity. Frontier technologies can establish the foundation for informational transparency, institutional trust, and data-driven decision-making, especially where access to conventional international mechanisms is restricted (Chandran & Narayanan, 2024). In this context, blockchain technology, as a decentralized and distributed ledger architecture, offers remarkable capabilities for energy management. Blockchain facilitates immutable data logging, enhances traceability, mitigates information asymmetry, and fosters mutual trust among disparate stakeholders. Furthermore, it enables peer-to-peer (P2P) energy trading networks and transparent transaction settlements, thereby boosting overall energy management efficiency by curtailing administrative friction and institutional risks (Abedpour et al., 2024).

Despite these potentials, no coherent, smart, and localized management model has yet been designed and implemented in Iran that simultaneously addresses industrial energy imbalances, the architectural prerequisites of blockchain technology, and the constraints imposed by sanctions. This conceptual and empirical void has caused industrial energy management decision-making to remain largely reactive, short-term, and bereft of comprehensive analytical underpinning.

1.1. Energy Imbalance

Energy imbalance designates a state in which no stable equilibrium exists between energy supply and demand within an economic, industrial, or national system. Under such conditions, energy generation and supply capacity fail to satisfy prevailing consumption requirements, precipitating chronic deficits across distinct time intervals. This imbalance manifests across multiple energy carriers, including electricity, natural gas, refined petroleum products, and other energy vectors. Its consequences typically materialize as service curtailments or outages, escalated operational costs, and diminished macroeconomic and industrial productivity (Bagheri Moghaddam et al., 2024).

Energy imbalance is not merely driven by physical resource scarcity; it predominantly stems from a confluence of structural, managerial, and economic determinants. Rapid demand escalation, deteriorating generation and transmission infrastructure, distortionary pricing regimes, chronic underinvestment in capacity expansion, and weak demand-side management constitute primary drivers. In many jurisdictions, inadequate alignment among energy policies, industrial expansion plans, and overarching economic strategies further amplifies this phenomenon (Safaei et al., 2025).

In the industrial domain, energy imbalance exerts extensive ramifications on manufacturing performance. Energy-intensive industries such as steel, cement, petrochemicals, and aluminum suffer the greatest disruption due to their continuous reliance on baseline energy flows. Production line shutdowns, capacity curtailments, elevated operational overheads, and the erosion of competitiveness in domestic and export markets are direct outcomes. Moreover, energy imbalances frequently compel facilities to resort to polluting and expensive backup fuel alternatives, entailing severe environmental and economic repercussions (Juybari et al., 2025).

From a managerial standpoint, energy imbalance reflects systemic failure in energy governance and integrated supply-demand orchestration. In recent years, scholars have emphasized that resolving energy imbalances requires innovative management paradigms and advanced technological instruments that restore durable equilibrium via enhanced information transparency, smart demand management, dynamic forecasting, and optimized resource allocation (Feng et al., 2022).

1.2. Energy Management

Energy management refers to a systematic suite of policies, procedures, and actions designed to optimize energy resource utilization, eliminate redundant consumption, enhance operational efficiency, and curtail energy expenditures across organizations and industries. Over recent decades, this concept has emerged as a cornerstone for realizing sustainable development goals, enhancing industrial competitiveness, and reducing the environmental footprint of energy utilization (Li et al., 2022).

At the enterprise level, energy management encompasses continuous processes such as metering, real-time consumption monitoring, load pattern diagnostics, conservation opportunity identification, equipment retrofitting, and the deployment of energy-efficient technologies. These measures empower organizations to optimize their energy consumption profiles and lower operational overheads. In addition, sound energy management significantly improves consumption predictability and strategic resource procurement.

With the proliferation of digital technologies, the scope of energy management has transformed fundamentally. Modern data-driven energy management systems, underpinned by the Internet of Things (IoT), artificial intelligence (AI), and big data analytics, enable continuous real-time oversight and automated, intelligent decision support. These systems automatically detect consumption anomalies, evaluate load profiles, and dynamically prescribe targeted conservation and optimization interventions (Narayanan et al., 2023).

At the macroeconomic scale, energy management encompasses national strategic planning and policy instruments to ensure long-term energy security. Governments leverage pricing signals, efficiency mandates, technological innovation frameworks, and infrastructure investments to maintain supply-demand balance. Within this architecture, energy management serves as a primary countermeasure against chronic energy imbalances and a catalyst for national energy system resilience.

1.3. Smart Energy Management

Smart energy management represents a modern paradigm within energy governance that leverages advanced digital technologies to monitor, analyze, and optimize energy utilization patterns. Under this framework, data related to energy generation, transmission, distribution, and end-use are captured and evaluated in real time, enabling operational and managerial interventions driven by intelligent algorithms and automated control systems (Androni et al., 2023).

In smart energy management systems, devices such as smart sensors, advanced metering infrastructure (AMI), IoT architectures, data mining, and machine learning models play central roles. These technologies facilitate the capture of massive, high-velocity datasets; through analytical processing, operators can identify behavioral consumption trends, forecast short- and long-term demand, and formulate optimal dispatch and conservation strategies. Consequently, industrial plants can govern their energy consumption with unprecedented precision and agility.

A hallmark of smart energy management is bidirectional interactivity between energy suppliers and consumers. In such networks, consumers dynamically calibrate their consumption profiles in response to grid conditions and real-time price signals. This dynamic demand flexibility mitigates peak-load stress on the grid, enhances supply-demand equilibrium, and prevents grid congestion.

Furthermore, smart energy management bolsters grid resilience. Predictive analytics and situational awareness mitigate the risk of widespread cascading blackouts and infrastructural failures. For these reasons, nations worldwide have prioritized massive capital deployment into smart energy infrastructure development.

1.4. Blockchain Technology

Blockchain technology represents a pivotal innovation in information architecture originally popularized through digital currency systems, whose utility has subsequently expanded across broad economic and industrial domains. Functionally, a blockchain is a distributed ledger wherein transactional records are cryptographically linked in consecutive blocks and distributed across a peer network. This decentralized architecture ensures data immutability, tamper resistance, and the elimination of single points of failure (Feng et al., 2022).

A core property of blockchain is ledger transparency: all transactions validated by consensus are irreversibly recorded and visible to authorized network participants. This attribute establishes distributed trust among network actors, mitigating dependency on centralized intermediary authorities. Furthermore, advanced cryptographic primitives guarantee data integrity and security.

Blockchain additionally facilitates the execution of smart contracts—self-executing code stored on-chain that automatically enforces the terms of an agreement when predetermined conditions are met. This capability streamlines diverse economic workflows, including automated energy settlement, supply chain verification, and multilateral clearance procedures.

In recent years, researchers have paid increasing attention to blockchain implementations within energy systems. Its decentralized, transparent, and secure operational framework positions it as an effective tool for enhancing data integrity, fostering trust among disparate market participants, and driving grid operating efficiency (Chen et al., 2023).

1.5. Applications of Blockchain Technology in the Energy Sector

Blockchain has emerged as a transformative technology in the energy sector, garnering intense focus from scholars and policymakers. By providing a decentralized, immutable platform for data logging and exchange, it enables superior operating efficiencies across energy ecosystems. In legacy energy systems, data handling and settlements are governed by centralized entities, which frequently introduces excessive transaction costs, information bottlenecks, opacity, and agency conflicts. Blockchain circumvents or minimizes centralized intermediaries, enabling direct, secure interactions among energy producers, grid operators, and consumers (Feng et al., 2022).

A primary energy application is the deployment of decentralized energy markets and peer-to-peer (P2P) energy trading. In these market architectures, prosumers and industrial facilities can directly trade surplus power—especially from on-site renewable installations—with other network participants. This peer-to-peer framework maximizes local market clearing, curtails wheeling and transaction costs, and improves distributed supply-demand matching. Moreover, deploying blockchain across energy data platforms fosters absolute data auditability and fine-grained consumption monitoring (Androni et al., 2023).

Another major application involves smart contracts for automated billing, capacity allocation, and financial settlement. Smart contracts execute programmatic agreements based on validated meter telemetry; once performance thresholds are verified, energy allocations or financial remittances occur autonomously. This automation eliminates administrative settlement delays, reduces transactional frictions, and mitigates contractual disputes (Chen et al., 2023).

In summary, blockchain technology enhances grid coordination, guarantees verifiable audit trails, resolves informational asymmetries, and builds trust across multi-stakeholder energy networks. It is widely recognized as a cornerstone technology for the realization of next-generation, resilient smart energy systems.

1.6. Sanction Constraints

Economic sanctions represent substantial external shocks capable of impairing national industrial and macroeconomic systems. Sanctions typically consist of coordinated financial, trade, technological, and investment embargoes designed to exert systemic economic pressure. These measures restrict access to international capital markets, advanced dual-use technologies, foreign export channels, and multinational industrial collaborations.

Within the energy domain, sanctions generate profound disruptions. Embargoes on modern machinery, industrial automation equipment, and software, coupled with the collapse of foreign direct investment (FDI) and restricted technical knowledge transfers, impede infrastructural renewal. In consequence, capital project development stalls, production costs surge, and overall energy system efficiency degrades.

In Iran, prolonged international sanctions have exerted severe repercussions on the energy sector and allied industrial complexes. Beyond restricting access to advanced energy management platforms, sanctions have obstructed strategic joint ventures and international financing for infrastructure expansion. Consequently, governing energy resources under these conditions necessitates innovative, resilient, and localized technological paradigms capable of mitigating external vulnerabilities (Moabi et al., 2024). In this setting, decentralized digital technologies such as blockchain offer viable avenues to offset sanction-induced frictions. By creating trustless, decentralized architectures for data and transactional exchange, they reduce dependency on centralized foreign software ecosystems and international clearinghouses, thereby facilitating direct, sovereign collaboration among domestic economic actors.

1.7. Energy Imbalance Management

Energy imbalance management encompasses the strategic suite of policies, instruments, and operational interventions designed to achieve sustainable equilibrium between energy supply and demand. When aggregate consumption outstrips system generation capacity, the resulting imbalance manifests as supply deficits, load shedding, and quota rationing. In these circumstances, imbalance management becomes the core mandate of energy policy.

A primary pillar of imbalance management is Demand-Side Management (DSM). DSM seeks to regulate aggregate consumption through conservation measures, load-profile optimization, and energy-efficient process adoption. Methodologies such as time-of-use (TOU) and critical-peak pricing, automated demand response (ADR) programs, and high-efficiency motor retrofits represent standard DSM interventions.

A complementary pillar involves industrial energy efficiency upgrades. Enhancing the thermodynamic efficiency of industrial plant equipment, deploying modern production technologies, implementing waste heat recovery systems, and optimizing plant process flows directly curtail baseline demand, mitigating grid stress (Omokara et al., 2025).

In recent years, the deployment of digital technologies and smart systems has been recognized as the most potent approach to managing imbalances. By providing high-frequency telemetry, advanced consumption diagnostics, and predictive load modeling, these systems empower industrial and grid operators to make rapid, optimal resource-dispatch decisions.

1.8. Energy Information Transparency

Energy information transparency designates the extent to which stakeholders maintain frictionless access to accurate, reliable, and up-to-date data regarding energy production, distribution, and end-use. Across many energy regimes, information opacity constitutes a primary root cause of allocative inefficiency. When accurate data concerning real-time generation, consumption rates, and system reserves remain inaccessible to decision-makers, strategic procurement and grid planning become erratic and ineffective (Abedpour et al., 2024).

Transparency serves as the cornerstone of sound energy governance. Access to timely, verifiable datasets empowers policymakers to formulate evidence-based policies and design effective market interventions. Furthermore, informational openness fosters organizational accountability among utilities and regulatory bodies, providing a basis for objective performance auditing.

At the organizational level, energy data transparency is equally imperative. Armed with granular consumption data, industrial managers can pinpoint conservation bottlenecks, eliminate parasitic losses, and optimize operational scheduling. Moreover, verifiable data allow executives to audit the empirical efficacy of energy conservation investments and execute corrective measures.

Due to its core architectural properties, blockchain technology plays a pivotal role in establishing energy data transparency. By logging energy generation and consumption metrics onto an immutable distributed ledger, it provides stakeholders with a single, verifiable version of truth, virtually eliminating the risk of data manipulation, retroactive alteration, or unauthorized data omission (Chandran & Narayanan, 2024).

1.9. Theoretical Foundations of the Research

A robust theoretical foundation provides a multidimensional framework for designing a smart energy imbalance management model. Sociotechnical Systems Theory accounts for the harmonization of technical and social dimensions; Network Governance Theory explains multi-stakeholder collaboration; Information Asymmetry Theory and Organizational Trust Theory illustrate the foundational necessity of transparency and trust; Digital Transformation Theory and Technological Innovation Theory identify blockchain's role in reshaping energy structures; and Energy Demand Management Theory provides the operational logic for industrial load optimization.

The theoretical perspectives informing the smart model for energy imbalance management in Iranian industries using blockchain under sanction constraints are summarized in Table 1.

Table 1. Role of Theoretical Frameworks in the Research Model

Theory	Description	Application in Energy Sector	Nexus with Blockchain
Sociotechnical Systems Theory	Emphasizes the simultaneous interaction of technical and social components in system performance.	Energy imbalances stem from the joint interaction of physical infrastructure with organizational, institutional, and human behavioral dynamics.	Blockchain serves as the technical backbone for immutable telemetry logging, real-time consumption auditing, peer exchange, and smart contract orchestration.
Network Governance Theory	Asserts that resolving complex problems necessitates collaborative coordination among interdependent, autonomous actors.	Effective energy governance requires multilateral alignment among government ministries, industrial firms, energy utilities, regulators, and technology providers.	With its decentralized topology, blockchain establishes a trust-minimized substrate for direct peer-to-peer data distribution and multi-party coordination.
Information Asymmetry Theory	Examines structural disparities in information access among actors and their adverse effects on market efficiency.	In energy systems, disparate access to generation telemetry, industrial consumption logs, and grid capacity metrics distorts optimal decision-making.	Blockchain drastically curtails information asymmetry by maintaining an immutable, transparent, and

			auditable distributed ledger accessible to all authorized participants.
Organizational Trust Theory	Focuses on confidence in the competence, integrity, and benevolence of counterparties in inter-organizational relationships.	Effective collaboration across the industrial energy value chain depends fundamentally on mutual trust among participating organizations and regulatory institutions.	Ledger transparency, end-to-end cryptographic traceability, and programmatic smart contract execution substantially eliminate counterparty risk and foster systemic trust.
Digital Transformation Theory	Analyzes the fundamental restructuring of organizational structures, operations, and value chains through digital technologies.	The energy domain is undergoing a paradigm shift from legacy, centralized models toward smart, data-driven, and distributed operational ecosystems.	Blockchain represents a foundational driver of this transition, providing decentralized market execution, tamper-proof audit trails, and autonomous settlement logic.
Energy Demand Management Theory	Focuses on demand-side optimization and active load modification to maintain sustainable supply-demand equilibrium.	Leverages instruments such as automated demand response, time-differentiated pricing, and AMI to shave peak grid loads.	Blockchain provides an immutable execution environment for logging load curtailments and autonomously distributing financial incentives or demand-response penalties.
Technological Innovation Theory	Evaluates the processes through which organizations create, adopt, absorb, and institutionalize novel technologies.	Modern industrial energy modernization depends on the successful institutional adoption of smart grids, IoT architectures, and distributed ledger systems.	As an organizational and process innovation, blockchain reinforces transactional security, informational integrity, distributed trust, and clearing efficiency in energy systems.

Source: Strbac et al., 2019; Casino et al., 2019; Goldstein et al., 2020; Hall et al., 2021; Huang et al., 2021; Sharaf et al., 2022; Robertson et al., 2022; Zhang et al., 2022; Kowalska et al., 2023; Sun et al., 2024.

1.10. Related Models and Conceptual Frameworks

Within energy management and the integration of novel technologies into infrastructure systems, numerous theoretical models and conceptual frameworks have been developed to explain resource optimization, efficiency improvements, and information transparency. Given the structural complexity of energy systems and the heterogeneity of market actors, adopting appropriate conceptual frameworks facilitates a deeper understanding of inter-variable interactions and informs the design of robust management systems. This section reviews the key models and conceptual frameworks relevant to energy management, blockchain integration, and energy imbalance resolution, as presented in Table 2.

Table 2. Related Conceptual Frameworks and the Role of Blockchain

Model or Framework	Definition and Nature	Key Components and Characteristics	Role of Blockchain
Smart Energy Grids Model	Advanced energy network architectures utilizing information and communications technology (ICT) to dynamically monitor, control, and optimize energy flows.	• Real-time telemetry acquisition and analytics • Bidirectional communication between suppliers and consumers • Dynamic demand response and load shifting • Predictive situational awareness via IoT, Big Data, and AI	• Augments telemetry data security and system integrity • Provides verifiable operational transparency • Facilitates decentralized peer coordination across grid participants
Blockchain-Based Peer-to-Peer (P2P) Energy Trading Model	A decentralized transactional model enabling direct energy exchange between generators and consumers without conventional central intermediaries.	• Decentralized network architecture • Distributed ledger logging of generation, consumption, and trades • Transactional auditability and lower transaction costs • Programmatic smart contract execution	• Delivers the distributed transactional backbone • Guarantees autonomous and deterministic contract execution • Eliminates dependency on centralized clearinghouses and intermediaries
Integrated Energy Management Model	A holistic management framework treating energy generation, transmission, distribution, and end-use as unified components of a single integrated system.	• Cross-sectoral alignment across the energy supply chain • High-fidelity, real-time data integration • Deployment of Advanced Metering Infrastructure (AMI), telemetry sensors, and centralized SCADA platforms	• Establishes a unified, decentralized data-sharing backbone • Fosters end-to-end transparency across institutional silos • Enhances operational synergy among utilities, regulators, and industrial end-users
Energy Data Governance Framework	A systematic structure of rules, standards, and mechanisms governing the secure collection, storage, dissemination, and utilization of energy data.	• Standardization of enterprise energy data architectures • Secure and auditable multi-stakeholder data exchange • Synchronized, role-based data access for market participants	• Enforces data immutability on distributed ledgers • Guarantees single-version-of-truth across all stakeholders • Eliminates data manipulation risks and reinforces inter-organizational trust

Source: Feng et al., 2022; Androni et al., 2023; Chen et al., 2023; Narayanan et al., 2023; Kowalska et al., 2023; Sun et al., 2024.

2. Methods

2.1. General Research Approach

Commensurate with the multifaceted and interdisciplinary nature of energy imbalances in Iranian industries, the methodology of this study is grounded in a mixed-methods (qualitative and quantitative) research design. This framework facilitates an in-depth identification of core components through qualitative instruments such as expert interviews, while enabling rigorous factor prioritization via the Analytic Hierarchy Process (AHP) implemented in Expert Choice software (version 11). According to the Frascati Manual guidelines (OECD, 2015), basic research expands the frontiers of fundamental knowledge without primary focus on immediate practical applications, whereas applied research is directed toward solving specific operational problems, and experimental development harnesses existing knowledge to design or substantially improve novel systems. Consequently, given its central objective of mitigating real-world industrial energy deficits and delivering actionable governance mechanisms, the present study falls squarely under applied research; furthermore, by designing a novel blockchain-based decision-support model, it bears an experimental-developmental character.

This taxonomy aligns with Kerlinger's (1986) classical distinction, which defines basic research as theoretical hypothesis testing and applied research as problem-solving within real-world operating environments, thereby firmly anchoring this investigation within applied operational scholarship. Moreover, Creswell (2014) posits that studies designed to address authentic organizational challenges through the development of actionable models, decision systems, or operational frameworks are inherently applied. Addressing the structural energy constraints facing Iranian industries through the formulation of an innovative decision architecture, this study embodies both applied and developmental characteristics. Integrating qualitative and quantitative analyses, it provides a methodologically rigorous foundation for scientific, data-driven decision-making.

2.2.Target Population and Expert Community

The target population comprises domain experts and thought leaders across energy economics, industrial engineering, blockchain technology, digital transformation, and national energy policymaking. Given the specialized nature of the research domain, participants were selected purposively using a snowball sampling strategy. In the initial screening phase, a candidate registry of 55 eligible professionals was identified. Following a rigorous evaluation of their scientific publications, professional credentials, and executive track records, 30 qualified specialists were finalized as the panel of experts. The profiles and selection criteria of the 30 participating experts are detailed in Table 3.

Table 3. Specifications and Selection Criteria for the Expert Panel (N=30)

Criterion / Attribute	Description
Panel Size	30 Experts
Sampling Technique	Purposive sampling targeting individuals with the highest domain relevance, coupled with snowball referrals; 30 finalized experts screened from an initial pool of 55 candidates
Selection Criteria	• Minimum of 10 years of professional or academic experience in energy, industrial management, or emerging technologies • Proven scholarly record (peer-reviewed papers, research grants) or executive leadership (senior administration, policy advisory) within energy management, including hands-on experience under sanction conditions
Domain Expertise & Disciplines	• Senior directors and chief energy managers across heavy industries (power generation, gas distribution, steel mills, petrochemical complexes, and energy-intensive manufacturing • Technical architects and researchers in blockchain protocols, distributed ledger systems, and industrial digital transformation

	• Senior policymakers, executive directors, and technical regulators from state energy agencies and industrial regulatory authorities
Result Validation Mechanisms	Enhanced credibility achieved through multidisciplinary expert heterogeneity, cross-group perspective triangulation, algorithmic inconsistency ratio verification (CR<0.10) across pairwise matrices, and sensitivity analysis in the decision model
Panel Composition Objective	Attaining a comprehensive, balanced, and realistic perspective by bridging technical, managerial, technological, and policy dimensions to design a resilient, localized, and actionable smart energy imbalance model for Iranian industries

Source: Research findings.

The curated composition of the panel guarantees balanced coverage across all operational dimensions of energy imbalances, ensuring that the resulting framework remains theoretically robust, technologically feasible, and aligned with industrial realities.

2.3. Data Collection Instruments

To collect and analyze empirical data, three complementary instruments are employed: systematic literature review, pairwise comparison questionnaires, and semi-structured expert interviews. In the exploratory phase, a comprehensive literature review was executed to delineate foundational dimensions and indicators for the conceptual framework. Building upon these constructs, a specialized multi-round Delphi questionnaire was developed and distributed, enabling pairwise evaluations and the derivation of priority weight vectors within Expert Choice (version 11). Concurrently, to enrich and contextualize the quantitative findings, semi-structured interviews were conducted with executive and academic authorities until theoretical saturation was attained. The synthesis of these three data streams establishes an integrated, localized architecture for industrial energy imbalance governance. The step-by-step workflow for the Delphi questionnaire development and administration is depicted in Figure 1.

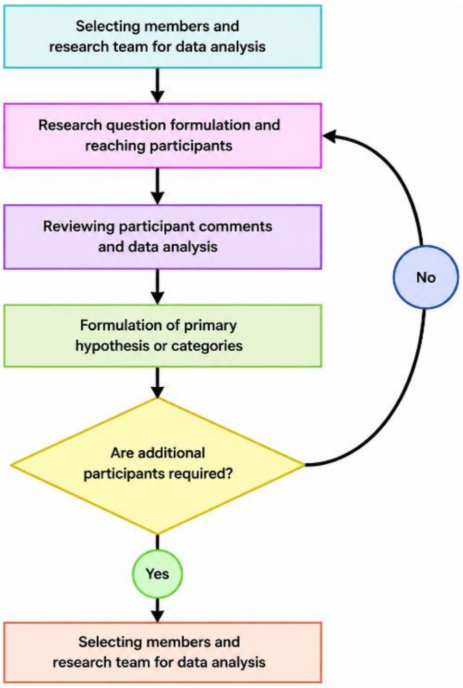


Figure 1. Delphi Questionnaire Development and Administration Workflow

Source: Research findings.

2.4. Sampling Strategy

A non-probability purposive sampling method combined with snowball referral was implemented. Given the highly specialized, cross-disciplinary intersection of energy systems, industrial economics, and decentralized blockchain architectures, domain competence took precedence over simple random sampling. An initial registry of 55 subject matter experts was compiled. Strict inclusion benchmarks were then applied: a minimum of ten years of documented leadership or academic research in energy governance, technology, or industrial policy. Ultimately, 30 top-tier specialists were retained for the study. The panel incorporates senior energy executives from major heavy industries, blockchain protocol architects, distributed system engineers, and regulatory policymakers. In the qualitative interview track, iterative sampling and interviewing continued dynamically until complete theoretical saturation was reached, ensuring no new conceptual categories emerged.

2.5. Validity and Reliability

To ensure rigorous validity and reliability within this mixed-methods inquiry, robust audit-trail strategies and analytical checks adapted to Delphi and semi-structured interview data were instituted. As Pourzandi et al. (2012) emphasize, maintaining methodological rigor in Delphi studies is an intricate undertaking requiring specialized qualitative validation protocols. Furthermore, validity and reliability in qualitative research are inextricably linked and reinforced through structured audit procedures (Ahmadi, 2008).

In the quantitative phase, construct and content validity of the pairwise comparison instrument were established via comprehensive alignment with theoretical literature and iterative panel pre-testing. To guarantee judgment reliability, the Consistency Ratio (CR) was mathematically monitored across all individual and aggregated pairwise matrices using Expert Choice software (version 11), ensuring compliance with the CR≤0.10 threshold. In addition, dynamic sensitivity analyses were conducted to verify the stability of output rankings against fluctuations in criterion weight.

Methodological credibility was reinforced through five core strategies:

- Investigator Responsiveness: Exercising intellectual reflexivity, analytical rigor, technical competence, and adaptive thinking across every phase of empirical data gathering and interpretation.
- Methodological Coherence: Maintaining tight alignment among research questions, overarching objectives, empirical datasets, and analytical algorithms through an iterative, constant-comparative feedback loop.
- Sampling Adequacy: Engaging verified subject-matter authorities rather than generalized respondents, sustaining sample size expansion until absolute theoretical saturation and expert consensus were confirmed.
- Concurrent Data Collection and Analysis: Iteratively analyzing incoming qualitative responses to identify emerging concepts, refining subsequent interview probes and data-collection protocols in real time.
- Theoretical Thinking: Continuously evaluating developing concepts and frameworks against emerging empirical data, refining theoretical touchpoints where structural discrepancies arose.

Beyond these internal checks, empirical validity was bolstered by drawing from a diverse multi-stakeholder panel, triangulating divergent professional viewpoints, calculating inter-rater consensus levels, enforcing matrix consistency checks, and conducting sensitivity analyses on the decision model. These integrated protocols ensure that the proposed model possesses robust scientific credibility and operational reliability for implementation across Iranian industrial environments.

3. Results and Discussion

The findings of this research are formulated in two parts: prioritization of indicators and model design. In the first part, by analyzing semi-structured interviews with 30 experts, the factors affecting energy imbalance in Iranian industries were identified and subsequently prioritized using the Analytic Hierarchy Process (AHP) in Expert Choice software version 11. As a result, four key dimensions comprising technical, managerial, policy-institutional, and technological (blockchain-based) dimensions formed the decision-making structure of the study. In the second part, relying on these dimensions, the final indigenous model for smart energy management was designed. Its mechanism is established upon a cycle of data ingestion from smart grids, recording and validation in a distributed ledger, decision-making via smart contracts, automated control of supply and demand, and continuous system feedback to realize transparent, decentralized, and efficient energy management under sanction conditions in the country's industries.

3.1. Extraction and Weighting of Dimensions and Indicators

3.1.1. Technical Dimension of Energy Management

The technical dimension pertains to infrastructure, energy generation and consumption technologies, energy efficiency, and the physical structure of energy networks. In fact, this dimension reflects the actual capacity of industries to manage energy supply and demand. Based on the analysis of expert interviews, the most critical criteria of this dimension are presented in Table 4.

Table 4. Identification and Weighting of Key Axes in the Technical Dimension of Smart Energy Imbalance Management

Axis	Weight	Rank
Digital and Data-Driven Infrastructure for Energy Management	0.282	1
Smartification of Energy Distribution and Consumption Networks	0.241	2
Energy Efficiency in Industrial Processes	0.180	3
Optimization of Energy Consumption in Equipment and Production Lines	0.150	4
Development and Utilization of Renewable Energy in Industries	0.146	5
Overall Inconsistency	0.01	—

Source: Research findings.

Interview data collected from several experts indicated that without reforming the technical structure of energy consumption in industries, no managerial policy can sustainably resolve the energy imbalance. Based on the logic of the Analytic Hierarchy Process, as observable in Table 4, and considering the infrastructural role of each factor in the smart management of energy imbalance alongside the feasibility of blockchain implementation in industries, the strategic significance of each axis in generating data, controlling consumption, and enabling smart management is evaluated first. In such a model, data infrastructure and grid smartening typically carry greater weight because smart monitoring, exchange, and management of energy are impossible without them. Subsequently, efficiency and optimization are positioned, followed finally by renewables, which primarily serve a complementary role.

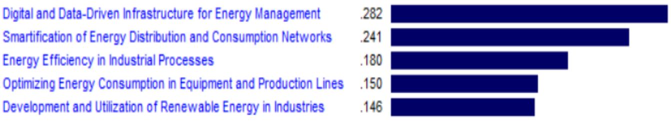


Figure 2. Identification of Key Axes in the Technical Dimension of Smart Energy Imbalance Management (Overall Inconsistency=0.01)

Source: Research Findings

In this regard, as observed in Figure 2, within the technical dimension of smart energy imbalance management, different axes hold varying weights in terms of importance and effectiveness. Accordingly, "Digital and data-driven infrastructure for energy management" with a weight of 0.282 ranks first, indicating the foundational role of data, digital systems, smart monitoring, and information analytics in the efficient management of energy supply and demand. In second place, the axis "Smartening of energy distribution and consumption networks" with a weight of 0.241 highlights the importance of developing smart grids, advanced metering infrastructure, and real-time management of energy flows in mitigating imbalances. Following that, "Energy efficiency in industrial processes" with a weight of 0.180 ranks third, representing the necessity of upgrading production technologies and reducing energy intensity in industries. Ranked fourth is "Energy consumption optimization in equipment and production lines" with a weight of 0.150, emphasizing equipment performance improvement, machinery modernization, and consumption management at the operational unit level. Finally, "Development and utilization of renewable energy in industries" ranks fifth with a weight of 0.146; although of strategic importance, its short-term impact is evaluated as lower compared to other technical components. Moreover, the overall inconsistency value is reported as 0.01, demonstrating an acceptable level of consistency in expert judgments and the validity of the results obtained in this analysis. Overall, these results indicate that approaches based on digitalization, grid smartening, and industrial efficiency enhancement represent the primary technical drivers for smart energy imbalance management.

3.1.2. Managerial Dimension

The managerial dimension refers to planning methods, internal industrial policy-making, management systems, and decision-making mechanisms in the energy domain. Therefore, the main criteria of this dimension extracted through expert interviews are presented in Table 5.

Table 5. Identification and Weighting of Key Axes in the Managerial Dimension of Smart Energy Imbalance Management

Axis	Weight	Rank
Implementation of Energy Management Systems in Industries	0.269	1
Energy Performance Monitoring and Evaluation Systems	0.221	2
Strategic Planning for Energy Consumption	0.192	3
Human Resource Training and Development in Energy Management	0.164	4
Organizational Culture Associated with Energy Efficiency	0.154	5
Overall Inconsistency	0.00	—

Source: Research findings.

This dimension demonstrates that even with adequate infrastructure in place, the lack of an efficient managerial system can exacerbate energy imbalances. According to the logic of the Analytic Hierarchy Process and the role of each component in realizing smart energy imbalance management at the organizational level, components establishing the formal management framework and energy decision-making system generally carry higher importance. As shown in Table 5, the establishment of an energy management system as the managerial foundation (such as the ISO 50001 standard) holds the highest priority. Following this is the energy performance monitoring and evaluation system, as controlling and rectifying consumption is unfeasible without data monitoring. Other factors such as planning, training, and organizational culture play complementary and reinforcing roles.

Figure 3. Identification of Key Axes in the Managerial Dimension of Smart Energy Imbalance Management (Overall Inconsistency=0.00)

Source: Research Findings

Based on the results of Figure 3, key axes within the managerial dimension of smart energy imbalance management were evaluated with different weights regarding importance and impact. Leading these axes, "Establishment of an energy management system in industries" with a weight of 0.269 ranks first, highlighting the vital importance of coherent managerial structures, systematic processes, and targeted policy-making in controlling and optimizing energy consumption. Subsequently, "Energy performance monitoring and evaluation system in industries" with a weight of 0.221 ranks second, emphasizing the necessity of establishing continuous oversight mechanisms, key performance indicators, and data-driven analysis of energy consumption. The axis "Strategic planning for energy consumption" with a weight of 0.192 and a third-place ranking signifies the need for a forward-looking approach, scenario building, and coherence in energy policies at both national and enterprise levels. Ranked fourth, "Human resources training and development in energy management" with a weight of 0.164 highlights knowledgeable and specialized human capital as a cornerstone of energy management system success. Finally, "Organizational culture related to energy efficiency" with a weight of 0.154 ranks fifth, showing that institutionalizing conservation values and environmental responsibility among employees and managers serves a complementary yet necessary role in the sustainability of the energy management system. The overall inconsistency value equals 0.00, denoting complete consistency in expert judgments and high validity of the analytical findings. Overall, these results indicate that establishing smart management systems, continuous monitoring, and strategic planning constitute the three primary pillars of success in smart energy imbalance management at the industrial management level.

3.1.3. Policy Dimension; Energy Policy-Making and Governance

The policy and institutional dimension refers to the structure of macro-level laws, regulations, and policies related to energy. Under sanction conditions, this dimension assumes particular significance, as energy policies can play a decisive role in resource management and reducing economic vulnerability. The key criteria of this dimension are presented in Table 6.

Table 6. Identification and Weighting of Key Axes in the Policy and Institutional Dimension of Smart Energy Imbalance Management

Axis	Weight	Ranking
Strengthening smart energy governance	0.241	1
Reforming the energy subsidy system	0.210	2
Government support policies for emerging energy technologies	0.189	3
Enhancing collaboration among government, industry, and the private sector	0.181	4
Developing legal frameworks for blockchain technology	0.179	5
Overall Inconsistency	0.00	

Source: Research Findings

Interviews gathered from several experts emphasized that without reforming policy and institutional frameworks, implementing emerging technologies such as blockchain at scale will not be feasible. Considering the Analytic Hierarchy Process approach and the specific conditions of energy management in Iran under institutional and sanction constraints, policy factors shaping the governance framework and operational regulations generally carry the greatest weight. As observed in Table 6, strengthening smart energy governance ranks first as the primary axis coordinating policies, data, and decision-making. Following this, reforming the energy subsidy system is of high importance, as the energy pricing structure directly influences industrial consumption patterns. Other factors, such as technology support, institutional collaboration, and blockchain legal frameworks, play complementary roles in executing the smart model.

Figure 4. Identification of Key Axes in the Policy and Institutional Dimension of Smart Energy Imbalance Management (Overall Inconsistency=0.00)

Source: Research Findings

The results of Figure 3 indicate that in the policy and institutional dimension of smart energy imbalance management, priorities are weighted such that the role of governance, policy-making, and institutional frameworks in smartly guiding energy markets and consumption is prominently highlighted. Leading these factors, "Strengthening smart energy governance" with a weight of 0.241 ranks first, demonstrating that coherent policy-making, data-driven decision-making, and agile governance structures exert the greatest impact on curbing energy imbalances. In second place, "Reforming the energy subsidy system" with a weight of 0.210 highlights the importance of redesigning pricing policies and reducing structural inefficiencies to align energy consumption incentives with reality. The axis "Government support policies for emerging energy technologies" with a weight of 0.189 ranks third, showing that the advancement of new technologies, including artificial intelligence, energy storage, and digital systems, requires sustained supportive backing. Furthermore, "Enhancing collaboration among government, industry, and the private sector" with a weight of 0.181 and a fourth-place ranking underscores cross-stakeholder synergy as a vital prerequisite for achieving smart energy management. Finally, "Developing legal frameworks for blockchain technology" with a weight of 0.179 ranks fifth, indicating that institutionalization for adopting emerging technologies across the energy value chain is still in its early stages, though its strategic importance is affirmed by experts. The overall inconsistency is reported as 0.00, demonstrating full consistency of judgments and high validity of the analytical results. Collectively, these findings emphasize that smart governance, institutional reforms, and supportive policy development represent three key pillars for effectively steering the energy system toward smart management and imbalance reduction.

3.1.4. Technological Dimension; Blockchain Technology and Smart Systems

One of the most prominent dimensions identified in this research is the technological dimension based on blockchain technology. As a decentralized technology, blockchain can provide a suitable platform for transparent, secure, and smart management of energy transactions. According to expert perspectives, the most critical applications of blockchain in industrial energy management are presented in Table 7.

Table 7. Identification and Weighting of Key Axes in the Technological Dimension (Blockchain Technology) of Smart Energy Imbalance Management

Axis	Weight	Ranking
Transparent and immutable recording of energy consumption data	0.293	1
Establishment of decentralized energy markets	0.220	2
Enabling direct energy exchange between producers and consumers	0.175	3
Increasing transparency in energy resource allocation and distribution	0.157	4
Reducing intermediation and administrative costs	0.155	5
Overall Inconsistency	0.01	

Source: Research Findings

Under sanction conditions, this technology can help reduce dependency on centralized systems and enhance the resilience of energy infrastructure. According to the logic of the hierarchy process and the core functions of blockchain technology in energy systems, as seen in Table 7, the most significant role of this technology in managing energy imbalance is providing transparency and immutable data recording, as all smart decision-making, energy markets, and consumption controls rely on verified data. Following that, establishing decentralized energy markets and enabling direct energy trading hold high importance by creating a new paradigm for energy exchange. Other components represent operational outcomes of this framework.

Figure 5. Identification of Key Axes in the Blockchain-Based Technological Dimension of Smart Energy Imbalance Management (Overall Inconsistency=0.01)

Source: Research Findings

The results of Figure 5 show that within the blockchain-based technological dimension of smart energy imbalance management, specific functions of this technology play a more prominent role in improving the efficiency and transparency of the energy system. Among these, "Transparent and immutable recording of energy consumption data" with a weight of 0.293 ranks first, indicating the importance of creating a reliable, tamper-proof, and distributed ledger-based data foundation for accurate consumption pattern monitoring and data-driven decision-making in energy management. In second place, "Establishment of decentralized energy markets" with a weight of 0.220 reflects blockchain's capability to shape modern energy market structures and reduce centralization in trading and distribution processes. Following this, "Enabling direct energy exchange between producers and consumers" with a weight of 0.175 ranks third, underscoring blockchain's role in facilitating peer-to-peer models and enhancing the efficiency of micro- and local-level energy interactions. Moreover, "Increasing transparency in energy resource allocation and distribution" with a weight of 0.157 ranks fourth, demonstrating that the adoption of this technology can make resource allocation processes more transparent and traceable. Finally, "Reducing intermediation and administrative costs" ranks fifth with a weight of 0.155; while recognized as an important benefit of blockchain, its direct impact on managing energy imbalances is evaluated as lower compared to other functions. The overall inconsistency value is reported as 0.01, indicating an acceptable level of consistency in expert judgments and the validity of the results. Overall, these findings reveal that the primary role of blockchain technology in smart energy imbalance management lies in generating data transparency, facilitating decentralized market formation, and providing a platform for direct energy transactions among various stakeholders across the energy value chain.

3.1.5. Key Dimension of Energy Imbalance Management

Managing energy imbalance in Iranian industries is a multidimensional issue requiring a comprehensive and integrated approach; the dimensions and components of this approach are presented in Table 8. The results obtained from analyzing the collected questionnaires indicate that among the dimensions identified in this research, the blockchain-based technological dimension is recognized as the most critical dimension.

Table 8. Identification and Weighting of Key Dimensions in Smart Energy Imbalance Management

Dimension	Key Axes	Weight	Ranking
Technological (Blockchain Technology)	- Transparent and immutable recording of energy consumption data - Establishment of decentralized energy markets - Enabling direct energy exchange between producers and consumers - Increasing transparency in energy resource allocation and distribution - Reducing intermediation and administrative costs	0.349	1
Technical	- Digital and data-driven infrastructure for energy management - Smartening of energy distribution and consumption networks - Energy efficiency in industrial processes - Energy consumption optimization in equipment and production lines - Development and utilization of renewable energy in industries	0.247	2
Managerial	Establishment of an energy management system in industries - Energy performance monitoring and evaluation system in industries - Strategic planning for energy consumption - Human resources training and development in energy management - Organizational culture related to energy efficiency	0.203	3
Policy and Institutional	Strengthening smart energy governance - Reforming the energy subsidy system - Government support policies for emerging energy technologies - Enhancing collaboration among government, industry, and the private sector - Developing legal frameworks for blockchain technology	0.201	4
	Overall Inconsistency	0.01	

Source: Research Findings

By synthesizing the Analytic Hierarchy Process results across the four primary dimensions and taking into account the views of experts in energy, industrial management, and information technology, the findings presented in Table (6) indicate that in smart energy imbalance management across Iranian industries, the policy-institutional dimension plays the greatest role, as legal frameworks, subsidy reforms, and energy governance provide the foundation for implementing other dimensions. Following that, the blockchain-based technological dimension ranks second as the technological core of the model. Furthermore, the technical and managerial dimensions rank subsequently, serving supporting roles in infrastructure deployment and industrial energy consumption management.

Figure 6. Identification of Key Dimensions in Smart Energy Imbalance Management (Overall Inconsistency=0.01)

Source: Research Findings

The results of Figure 6 show that in the final synthesis of key dimensions for smart energy imbalance management, the blockchain-based technological dimension—led by the axis "Transparent and immutable recording of energy consumption data"—holds the highest weight of 0.349 and ranks first. This highlights the foundational role of data transparency, distributed ledgers, and blockchain trust in establishing a smart infrastructure for energy imbalance management. Following this, the technical dimension—led by "Digital and data-driven infrastructure for energy management" with a weight of 0.247—ranks second, emphasizing the critical importance of digitalization, smart grids, and real-time monitoring infrastructure in efficient energy management. In third place, the managerial dimension—led by "Establishment of an energy management system in industries" with a weight of 0.203—demonstrates the necessity of coherent management structures, systematic processes, and KPI-based oversight in energy-intensive industries. The policy and institutional dimension—led by "Strengthening smart energy governance" with a weight of 0.201—ranks fourth, emphasizing that integrated policy-making, institutional reforms, and state support for emerging technologies play an essential yet complementary role in realizing smart energy imbalance management. The overall inconsistency value equals 0.01, demonstrating a desirable level of consistency in expert judgments and the reliability of the synthesized analytical results. In conclusion, these findings demonstrate that data transparency, digital infrastructure, robust management systems, and smart governance constitute the four main pillars in deploying a comprehensive approach to smart energy imbalance management.

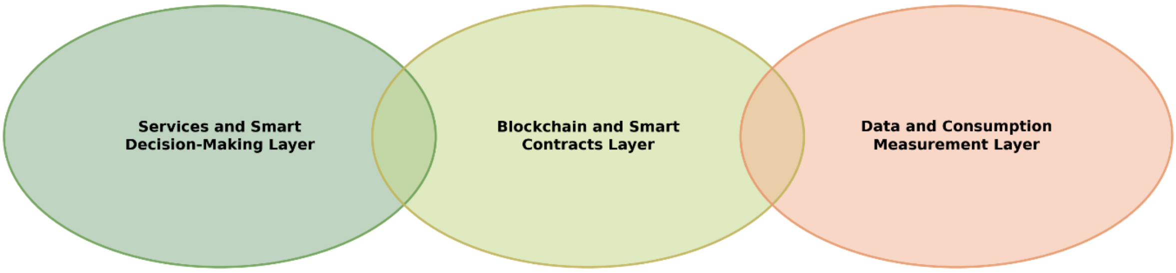


Figure 7. Macro Architecture of the Blockchain Model

Source: Research Findings

3.2.2. Structural Components of the Blockchain Model

Based on the research findings, the five structural components presented in Figure 8 have been designed as the main pillars of the model.

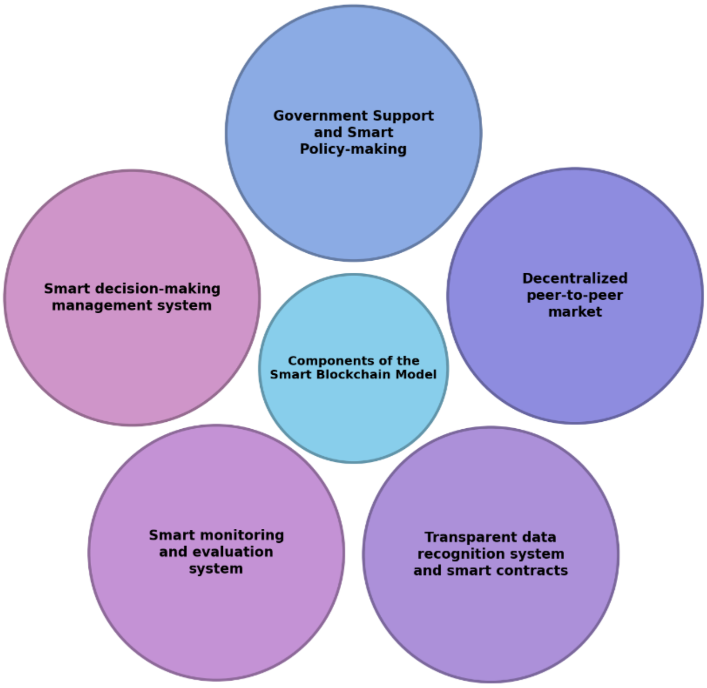


Figure 8. Structural Components of the Blockchain Model

Source: Research Findings

3.2.3. Operational Mechanism of the Blockchain Model in Energy Imbalance Management

The comprehensive mechanism of the model is executed in five steps, as presented in Table 9.

Table 9. Operational Mechanism of the Blockchain Model in Energy Imbalance Management

Step	Description
Step 1: Data Collection and Validation	All meters, sensors, and systems transmit energy data in an encrypted manner to the blockchain network. The data is validated by network nodes (representatives of industries, the Ministry of Energy, etc.).
Step 2: Recording in Distributed Ledger	Upon validation, the data is recorded in blocks, establishing an immutable and tamper-proof history of energy consumption.
Step 3: Execution of Smart Contracts	Smart contracts automatically execute energy rationing, implement consumption restrictions during peak hours, apply dynamic pricing, execute peer-to-peer (P2P) trading, and manage seasonal or emergency energy allocation based on the recorded data.
Step 4: Smart Energy Imbalance Analysis	Using transparent and verified data, the smart analytics system identifies imbalances, analyzes root causes, forecasts consumption patterns, and recommends corrective policies.
Step 5: Feedback and Policy Optimization	The analysis results are communicated to policy-making institutions (Ministry of Energy, industries, Tavanir Company, etc.) to improve energy policies and pricing structures.

Source: Research Findings

3.2.4. Designing the Model for the Role of Blockchain in Mitigating Energy Imbalance under Sanction Conditions

In addition to serving as a modern mechanism for fortifying infrastructure under sanction conditions, blockchain technology enables decentralized management independent of foreign infrastructure by establishing full consumption transparency, reducing errors and violations, and increasing grid resilience against cyber attacks. By facilitating intermediary-free transactions and reducing reliance on sanctioned financial systems via energy tokens, this technology transforms the country's energy management structure into an autonomous, resilient, and efficient instrument in the face of international restrictions. The smart blockchain-based energy imbalance management model is illustrated in Figure 9.

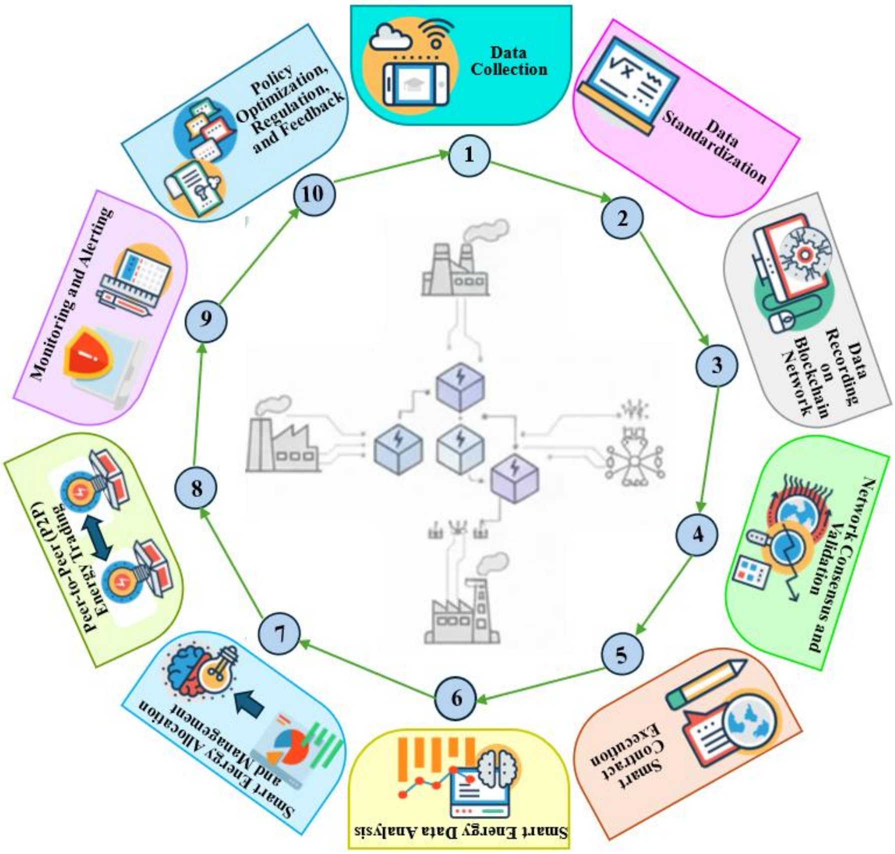


Figure 9. Smart Blockchain-Based Energy Imbalance Management Model

Source: Research Findings

3.2.5. Stages of the Designed Model

The stages of the designed model for "Smart Blockchain-Based Energy Imbalance Management" are outlined in Table 10.

Table 10. Stages of the Designed Model

Stage / Stage Number	Main Activities and Measures	Outputs, Characteristics, and Stakeholders
Energy Data Collection (1)	Receiving energy consumption and generation data from smart meters, IoT sensors, SCADA systems for monitoring and managing industrial processes, and industrial production and maintenance management systems	Output: Raw energy data stream
Data Standardization and Preprocessing (2)	Data cleaning, including removal of errors, incomplete records, and duplicate data; integration of data from diverse sources; conversion of data into a standardized format ready for blockchain recording	Output: Standardized data ready for ledger registration
Data Registration on Blockchain Network (3)	Converting energy data into ledger transactions; creating new transaction blocks; appending blocks to the blockchain ledger	Characteristics: Transparency, immutability, and full auditability/traceability of energy generation and consumption history
Network Validation and Consensus (4)	Verifying data and block validity by authorized network nodes, including industry representatives, power utility companies, and regulatory bodies; utilizing appropriate consensus algorithms such as Practical Byzantine Fault Tolerance (PBFT) or Proof of Authority (PoA)	Ensuring that only verified and legitimate data enters the blockchain ledger
Smart Contract Execution (5)	Automated enforcement of energy management rules, including consumption quota allocation for each industry, curtailment during peak load hours, and dynamic pricing based on grid status; automated execution of energy transactions and settlements according to predefined rules	Transparent, automated execution without the need for continuous human intervention
Smart Energy Data Analytics (6)	Analyzing blockchain-recorded data utilizing data mining, machine learning, and future demand forecasting techniques	Outputs: Identification of consumption patterns; detection of imbalance points (deficits or surpluses); extraction of energy efficiency indices across industries
Smart Energy Management and Allocation (7)	Regulating and reallocating energy among industries based on energy consumption intensity, efficiency levels, and industrial/national priorities; dynamic and real-time updating of quotas using smart contracts	Optimal, dynamic, and equitable energy allocation across industrial sectors
Peer-to-Peer (P2P) Energy Trading (8)	Enabling direct energy trading between energy-surplus and energy-deficit industries; conducting transactions without centralized intermediaries over the blockchain; automated and transparent settlement via smart contracts	Establishment of a direct, transparent, and decentralized energy market
Energy Imbalance Monitoring and Alerting (9)	Real-time monitoring of energy consumption, generation, and losses; rapid identification of imbalances at the industry, industrial park, or regional grid level; dispatching alerts to plant managers, grid operators, and energy policy-makers	Rapid, targeted response to energy imbalance occurrences
Feedback, Policy Optimization, and Regulation (10)	Utilizing analytical outputs to refine energy pricing structures, revise rationing schemas and incentives, and formulate new policies for efficiency improvement	Closing the feedback loop: Outputs of this stage re-enter the decision-making cycle and smart contracts. The system progressively and adaptively mitigates energy imbalances through continuous learning.

Source: Research Findings

4 .Conclusion

This research was conducted with the aim of designing a smart energy imbalance management model for Iranian industries based on blockchain technology and within the context of sanction constraints. The combination of qualitative and quantitative approaches, analysis of expert perspectives, and multi-criteria modeling provided the foundation for an applied model tailored to the country's infrastructural conditions. The findings revealed that energy imbalance is a multidimensional and deeply rooted phenomenon linked to inefficiencies in data and measurement infrastructure, lack of transparency, managerial and supervisory weaknesses, absence of smart allocation and pricing mechanisms, and the scarcity of decentralized, sanction-resilient platforms.

Based on the results, the proposed model is grounded on five primary components: a transparent energy data registration system, a decentralized market and P2P exchange framework, a smart allocation and rationing system, a grid status and imbalance analytics system, and a smart-contract-based mechanism for automated energy management. Analyses indicated that deploying these components can significantly reduce human intervention, errors, administrative corruption, hidden losses, and operational irregularities in industrial energy management. Furthermore, linking authenticated real-time data to smart contracts enables agile, responsive, and precise decision-making in response to demand fluctuations, emergencies, and new energy policies.

In addressing the research questions, it was determined that the factors affecting energy imbalance in Iranian industries span technical, economic, managerial, institutional, and technological domains, and blockchain technology can enhance the management of this imbalance by providing transparency, tamper-proof data recording, elimination of intermediaries, and facilitation of decentralized transactions. Under sanction conditions, priority solutions center on technological self-reliance, indigenization of energy platforms, smart pricing, data integration, and the establishment of P2P mechanisms. Overall, this research demonstrated that blockchain can transition Iran's industrial energy management from a centralized, high-cost framework into a transparent, smart, participatory, and sanction-resilient model.

Based on the research findings, a set of strategic recommendations is proposed across four main levels, asserting that the realization of smart energy imbalance management in the country's industries requires comprehensive synergy among policy-makers, industrial managers, technology developers, and researchers. At the policy level, priorities include formulating regulations and a national smart management roadmap, developing a national energy blockchain infrastructure, reforming the pricing model, and providing financial incentives for industries. At the industrial management level, focus is placed on integrating data systems, deploying smart metering, and utilizing P2P energy markets to optimize consumption and eliminate waste. Meanwhile, technology developers are tasked with designing indigenous blockchain platforms with lightweight consensus algorithms, formulating managerial smart contracts, and strengthening network cybersecurity. Finally, to further advance this approach, future researchers should undertake comparative model studies, analyze the economic impacts of decentralized markets, explore the integration of blockchain with artificial intelligence, and evaluate the feasibility of industrial energy tokenization.

Author Contributions

All authors contributed equally to the conception, preparation, and writing of this manuscript.

Conflict of Interest

S.A. Razavi, in the capacity of Editor-in-Chief, had no involvement in the selection of reviewers or the management of the peer-review process, and the other authors, while observing publication ethics in referencing, declare the absence of any conflict of interest.

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Data availability

This article does not contain any Supplementary Material.

AI Used Statment

The authors retain full responsibility for the accuracy, originality, integrity, legality, and ethical compliance of all text, data, tables, figures, analyses, references, and conclusions, and have verified all AI-assisted outputs. Any fabrication, falsification, manipulation, plagiarism, copyright infringement, or other misuse of AI remains solely the responsibility of the authors and does not transfer or diminish their accountability for the published work.

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