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Integration of Artificial Intelligence and Blockchain: Combining Two Transformative Technologies in Iran's Power Sector

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ABSTRACT

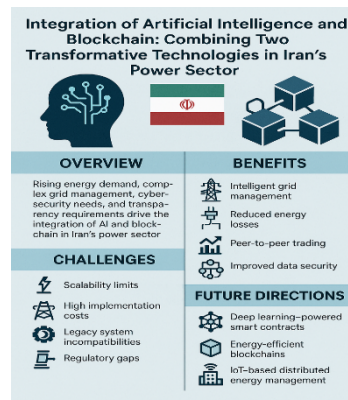
The aim of this study is to examine how the integration of two innovative technologies Artificial Intelligence (AI) and Blockchain can transform and enhance the efficiency, security, and transparency of Iran's electricity sector. Accordingly, this research adopts a descriptive–analytical approach based on a systematic review of national and international academic sources to identify the capacities, challenges, and strategies for integrating these technologies into the country's energy system. The findings indicate that AI, through predictive analytics, adaptive learning, and process optimization, can make electricity network management smarter and more efficient. Conversely, blockchain technology provides a transparent, secure, and decentralized platform for energy data exchange. The synergy between these two technologies can lead to reduced energy losses, facilitation of peer-to-peer energy trading, enhanced data security, and improved grid sustainability. However, several barriers hinder this integration, including scalability limitations, high implementation costs, incompatibility with legacy infrastructure, legal and regulatory challenges, and a shortage of skilled professionals. Finally, the study proposes strategic measures such as developing supportive policies, employing deep learning–based smart contracts, adopting low-energy blockchain solutions, and expanding IoT-based energy management systems. These actions can pave the way for the establishment of an intelligent, efficient, and sustainable electricity infrastructure in Iran.

Keywords:

ArtificialIntelligence,Blockchain,Iran'sPowerIndustry,DigitalTransformation,Energy Security and Efficiency.

Graphical Abstract

AI and Blockchain in Iran's Energy



1 Introduction

In recent years, the power sector has been facing increasing challenges such as rising energy demand, grid instability, cybersecurity threats, and environmental pressures. In Iran, in particular, energy crises characterized by widespread blackouts and aging infrastructure have underscored the urgent need for digital transformation in the energy industry [1]. Simultaneously, emerging technologies like Artificial Intelligence (AI) and Blockchain have been identified as promising tools for enhancing transparency, efficiency, and security in smart grid systems [2].

At the international level, numerous studies have examined the convergence of AI and Blockchain technologies in the context of smart grids. Research shows that AI can enhance grid performance through load forecasting, demand-side analytics, and system automation, while Blockchain can secure transactions, enable smart contracts, and support decentralized energy trading systems [3, 4]. For example, integration of these technologies in prosumer-based energy markets has been shown to facilitate peer-to-peer (P2P) trading and improve energy distribution management [5]. Furthermore, AI-Blockchain synergy is being explored for its potential to strengthen grid cybersecurity and develop self-healing systems against cyberattacks [6, 7]. Figure 1 illustrates various components of the smart grid.

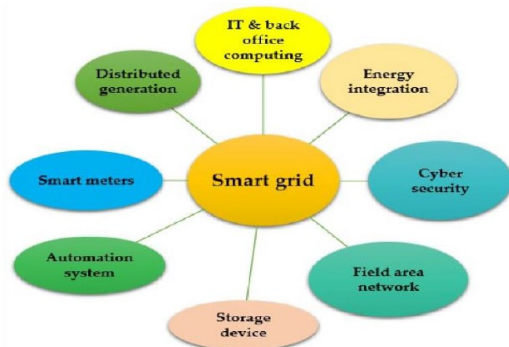


Figure 1. Essential components of the Smart grid

In Iran, although early initiatives such as the "FAHAM" smart metering program were launched to reduce energy loss and improve operational efficiency [8], few academic efforts have focused on the integrated application of AI and Blockchain in the country's electricity sector. Additionally, isolated case studies on the impact of cryptocurrency mining have revealed how unregulated digital activities can intensify pressure on the national grid [1, 9].

Despite the growing body of global literature focused on technical architectures and implementation models [3, 6, 7], there are significant research gaps specific to the Iranian context that remain underexplored:

1. Limited analysis of legal, regulatory, and policy challenges regarding the domestic deployment of AI and Blockchain.

2. Lack of spatial and economic assessments of Blockchain-based energy markets in Iran.
3. Insufficient attention to risk-based cybersecurity frameworks suitable for outdated infrastructure.
4. A lack of investigation into the feasibility of these technologies under international sanctions and equipment limitations [2, 9].

This paper offers a novel contribution by critically reviewing both domestic and international literature and presenting a multi-dimensional perspective technical, economic, security focused, and policy oriented on the integration of AI and Blockchain in Iran's power sector. The main innovations include:

1. A contextualized framework for understanding the technological compatibility of AI-Blockchain convergence with Iran's electricity infrastructure.
2. A comparative analysis of the legal, institutional, and infrastructural gaps impeding large-scale adoption in Iran.
3. A case-based discussion on cryptocurrency mining as an example of unintended technological impact on national grids; and
4. Practical policy recommendations and future research directions tailored to Iran's strategic energy goals.

The overarching aim of this critical review is to examine how the integration of AI and Blockchain can enhance transparency, efficiency, and security within Iran's power system. The article seeks to answer the following key questions:

1. In what ways can the combined application of AI and Blockchain technologies contribute to solving critical challenges in Iran's electricity sector?
2. What structural, legal, and operational barriers exist for their effective adoption?
3. Which strategies, models, or policy frameworks are best suited for implementation under Iranian conditions?

To address these questions, this review adopts a systematic approach to synthesize and critically analyze both global and local research, while also evaluating existing case studies to provide evidence-based insights for guiding technological and regulatory decision-making in Iran's power sector. By integrating theoretical analysis with empirical evidence, the study establishes a coherent framework for understanding the opportunities, challenges, and practical pathways for the integration of emerging technologies in the electricity industry, thereby laying the groundwork for the analytical discussion and actionable recommendations presented in the subsequent sections.

2 Methodology

This study uses a systematic and library review approach to investigate the integration of artificial intelligence and

blockchain technologies in the Iranian energy sector. The aim is to collect, analyze, and classify scientific evidence to identify opportunities, challenges, and strategic solutions in the country's electricity grid.

2.1 Study Framework

The study was designed based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) framework to ensure transparency and repeatability of the stages of identifying, screening, selecting, and analyzing articles.

2.2 Data Sources and Search Engines

To collect information, international scientific databases including Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar were reviewed. Also, SID, Magiran, and ISC databases were used to cover Persian sources and Iranian industrial reports.

2.3 Search Strategy and Keywords

Search based on a combination of keywords related to:

1. Artificial Intelligence: Artificial Intelligence, Machine Learning, Deep Learning
2. Blockchain: Blockchain, Distributed Ledger, Smart Contracts
3. Energy Sector: Power Sector, Smart Grid, Energy Management

Boolean operators (AND, OR, NOT) were used to combine concepts and limit results to relevant articles. The search time frame was 2010 to 2025 and the sources were limited to Persian and English languages.

2.4 Inclusion and Exclusion Criteria

1. Inclusion Criteria: Scientific articles and industry reports related to the application of AI and Blockchain in energy management and power grid, published within the specified time period.
2. Exclusion Criteria: Unrelated articles, lacking sufficient data, non-peer reviewed preprints, and sources with low credibility were excluded.

2.5 Article Screening and Selection Process

1. Initial Identification: 1,320 articles were identified in the initial search.
2. Title and abstract screening: 432 irrelevant articles were removed.
3. Full text review: Another 78 articles were excluded due to low quality or insufficient data.

4. Final selection: Finally, 106 valid articles and reports were selected for the final analysis.

2.6 Data extraction and analysis

The following information was extracted for each article:

1. Research objectives
1. Technologies used
2. Applications
3. Benefits and challenges
4. Proposed solutions

The data were analyzed in the form of tabulation and thematic and presented in three main areas:

1. Smart grid management
2. Data security and transparency
3. Energy trading based on new technologies

2.7 Quality and credibility assessment

The quality of the articles was measured by the following criteria:

1. Journal credibility and scientific review
2. Number of citations
3. Research methodology
4. Data comprehensiveness

2.8 Limitations

Limitations of the study included incomplete access to some domestic sources, language differences, and time constraints in the search. These limitations were taken into account in the final analysis

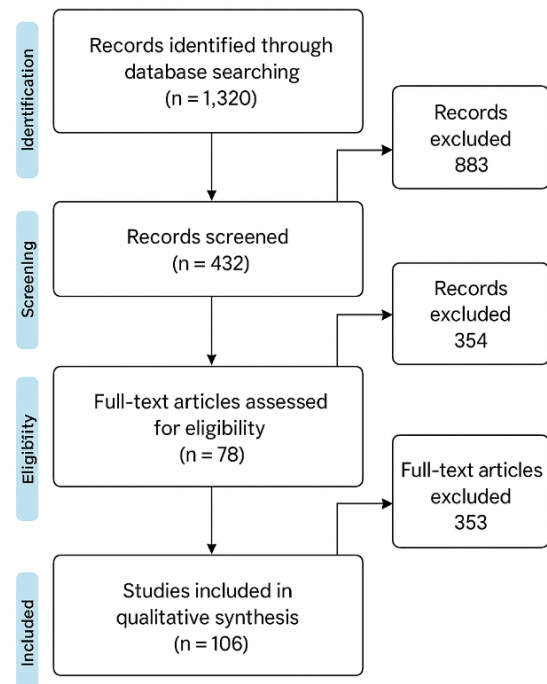


Figure 2. Research Methodology Using the PRISMA Framework

3 Necessity of Integrating Emerging Technologies in Iran's Power Industry

Iran's power sector is facing profound and persistent challenges, including outdated infrastructure, significant energy loss, an imbalance between supply and demand, heavy reliance on fossil fuels, and weak resilience to crises. These issues have intensified in recent years. For instance, during the winter of 2023–2024, widespread power outages were reported in several cities. Investigations revealed that a portion of the crisis was due to illegal cryptocurrency mining, which drew an estimated 600 megawatts from the national power grid [10].

In response, certain remedial measures were introduced by power authorities, most notably the implementation of the national smart metering program (known as FAHAM), which aims to install over 30 million smart meters by the end of 2025 [11]. While this initiative is an important step toward improved consumption monitoring and data transparency, it remains insufficient due to infrastructural limitations and the lack of real-time analytics. Consequently, the adoption of advanced technologies such as Artificial Intelligence (AI) and blockchain has become increasingly necessary to enhance the efficiency, security, and genuine intelligence of the grid.

Artificial intelligence offers powerful tools for managing supply and demand by analyzing consumption data, forecasting load patterns, and detecting abnormal behaviors within the power system. For instance, the use of machine learning models like recurrent neural networks (RNNs) and genetic algorithms in electricity demand forecasting has improved prediction accuracy by up to 25% compared to traditional models [12]. Iran has also announced the launch of six national AI megaprojects aimed at reducing network imbalances and optimizing consumption in residential and industrial sectors [13].

On the other hand, blockchain technology, as a decentralized and tamper-proof data registry, can significantly contribute to establishing trust, transparency, and security in energy transactions. Through smart contracts, peer-to-peer (P2P) electricity trading becomes feasible a model successfully implemented in international projects such as Brooklyn Microgrid in the United States and Power Ledger in Australia [14].

The true potential emerges when these two technologies are integrated. Blockchain can provide secure, verified, and immutable data to AI algorithms, while AI can make automated, optimized decisions for grid management, which can then be executed as smart contracts on blockchain networks. This convergence leads to the development of next-generation power grids so-called Smart Grid 2.0 characterized by autonomy, security, reliability, and cyber-resilience [15]. International policy analyses, such as those by GlobalData, emphasize that countries like China, Germany, and India are simultaneously investing in AI and blockchain and view their convergence as a cornerstone of digital transformation in the energy sector over the coming decade [16]. In Iran, although

isolated pilot projects exist in both domains, there is still no evidence of systematic, policy-driven integration at a national level. This gap underscores the urgent need for comprehensive strategies in applying AI and blockchain within the power industry.

In conclusion, the current state of Iran's power sector, along with successful international experiences, indicates that purposeful and well-planned integration of AI and blockchain is the only viable path toward a more efficient, intelligent, responsive, and future-proof electricity system. This necessity forms the core motivation for the present review article, which aims to critically examine the existing literature, identify research gaps, and outline potential paths forward.

4 Review of the Background and Applications of Artificial Intelligence and Blockchain in the Power Industry

In recent decades, rapid advancements in information and communication technologies have led to the emergence of transformative tools such as Artificial Intelligence (AI) and blockchain. Each of these technologies, independently, has brought about significant changes in various sectors, especially the power industry. Reviewing their backgrounds and applications in this field helps illuminate development pathways while clarifying existing strengths, limitations, and challenges.

4.1 AI in the Power Sector: Historical Context and Development

Artificial Intelligence has been used in the power sector since the 1980s, initially applied to load forecasting, demand-side management, and fault detection in power grids [17]. With increasing computational power and the evolution of machine learning algorithms, AI applications have expanded to more complex tasks, including generation optimization, predictive maintenance, and intelligent distribution network management [18].

For instance, in a project implemented by General Electric in 2020, deep learning algorithms were used to improve urban electricity consumption forecasting and optimize grid operations, resulting in a 15% reduction in operational costs [19]. In Iran, the state-run Tavanir Company and several academic institutions have also undertaken projects on load forecasting and energy optimization using AI, indicating growth and interest in this area [20].

4.2 Blockchain in the Power Sector: Foundations and Early Applications

Blockchain, initially known for its use in Bitcoin in 2008, found its way into the energy sector around 2015 [21]. One of the earliest applications involved creating peer-to-peer (P2P)

energy trading systems and ensuring transparent recording of electricity purchase contracts. In Australia's Power Ledger project, blockchain has been used to facilitate renewable energy transactions between small-scale producers and consumers [22].

By enabling immutable data records, transparency, cybersecurity, and the elimination of intermediaries, blockchain has improved trust in energy transactions and enhanced system efficiency. In China, various blockchain-based platforms have been developed to track and certify renewable energy production, enabling more accurate policymaking to reduce emissions [23].

4.3 Integrated Applications of AI and Blockchain in the Power Industry

Based on data, AI mines knowledge from data, while blockchain is essentially a data storage method, or “hyper ledger”, which supports the realization of data intelligence. And blockchain technology can ensure reliable data to a certain extent, share data under the condition of protecting data privacy, provide high-quality data for AI modeling, and thus improve the accuracy of the model. Therefore, the two technologies that are closely related to data can be effectively combined to complement each other and achieve technological upgrading (Figure 3) [82,83].

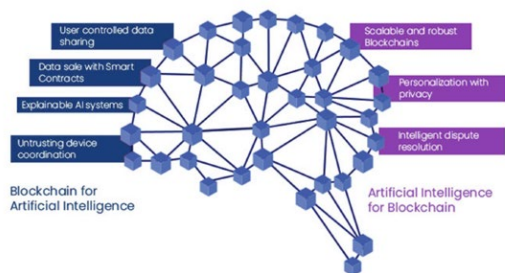


Figure 3. Integration of AI and Blockchain

Blockchain technology has the characteristics of being distributed, open, transparent, traceable, and difficult to tamper with. It can improve the authenticity, relevance and effectiveness of data used in AI applications by combining multiple technologies, such as distributed data storage, point-to-point transmission, consensus mechanisms, and encryption algorithms. Also, it can ensure the intelligence level of AI models in three different aspects, i.e., data, computing power and algorithms, innovate the collaborative mode and computing paradigm of AI technology, and build a new AI ecosystem. Based on the blockchain, AI can realize decentralized intelligent joint modeling and provide users with flexible computing capabilities to meet specific application needs. The smart contract in a blockchain is essentially a piece of code that implements a certain algorithm, which can be made more intelligent by AI technology. AI has the characteristics of being intelligent and automatic. Through optimization and simulation, AI algorithms can promote the

natural evolution and data sorting of the blockchain, effectively prevent the occurrence of bifurcation of linked nodes, and more efficiently handle the operation of the blockchain. For example, AI algorithms can transform traditional contracts into smart contracts, effectively solving the problems of security, ease of use and reliability. At the same time, decentralized learning systems such as “joint learning” introduced by AI can be used to solve the problem of redundant information on the blockchain, which can improve the extensibility and efficiency of the blockchain. Given their interdependence with each other, There’s no reason not to believe it will be a good idea to fuse AI and blockchain technologies [82-85].

A growing trend in recent years has been the integration of AI and blockchain to maximize their combined advantages. In smart distribution networks, for example, blockchain provides a secure platform for storing and exchanging consumption and generation data, which AI systems can analyze to make informed and optimized decisions.

One European project successfully demonstrated how the convergence of these technologies enhanced load forecasting and demand-side management in microgrids. This integration particularly proved effective under volatile load conditions, improving grid stability and reducing maintenance costs [24].

4.4 Challenges and Limitations

Despite their benefits, deploying AI and blockchain in the energy sector faces significant obstacles. These include the need for advanced digital infrastructure, a shortage of specialized human resources, data privacy concerns, and scalability issues [25]. In Iran, these challenges are further compounded by international sanctions and gaps in digital readiness, slowing down the adoption of these technologies [26,71,103].

5 Practical Applications of the Integration of Artificial Intelligence and Blockchain in the Power Industry

The integration of Artificial Intelligence (AI) and blockchain, as two transformative technologies in the power industry, not only enhances the individual benefits of each but also leads to solutions that are unattainable without their synergy. This technological combination enables the creation of intelligent, automated, transparent, and secure systems that effectively address complex challenges such as consumption imbalance, renewable resource management, cybersecurity, and energy transaction settlements.

One of the most important applications of this integration lies in Peer-to-Peer (P2P) Energy Trading. In this model, consumers can buy or sell electricity directly to small producers or other consumers. Here, blockchain provides the platform for transactions, while AI optimizes the matching of supply and demand through consumption pattern analysis and

intelligent pricing. For example, the Brooklyn Microgrid project in the United States enabled solar energy trading among neighborhood residents without utility company intermediaries. Machine learning algorithms forecasted consumer behavior, and blockchain ensured the security and transparency of transactions [27].

In the domain of Smart Management of Renewable Energy Resources, the AI-blockchain combination has also proven highly effective. Renewable energies like solar and wind present challenges in planning and grid injection due to their variability. AI models predict production and consumption to assist decisions on storage or injection timing, while blockchain provides a transparent and traceable recording process for production and transfer. The Pylon Network project in Spain utilized these technologies to record solar power generation and consumption and to create a transparent clean energy marketplace. AI-based prediction algorithms were employed, and all transactions were stored on blockchain for reliability and trustworthiness among regulators, consumers, and producers [28].

In Predictive Maintenance, this integration plays a key role. AI analyzes sensor data installed on critical network equipment such as transformers, switches, and cables to detect impending faults. When these data are recorded on blockchain, they become tamper-proof and can be used for validating equipment performance over time. This feature is significant for insurers, government regulators, and company shareholders. For instance, Siemens in Europe employed a combination of deep learning algorithms and blockchain technology for predictive maintenance of high-voltage equipment, reducing emergency repair costs by 30% [29].

Another practical application is in Demand Response Management. AI analyzes consumption patterns and suggests load reduction during peak periods. Blockchain executes smart contracts that automatically reward users for lowering consumption. The Electron project in the UK employed this model to enable residential participation in demand response programs, providing energy tokens as incentives. Smart contracts ensured fast and accurate execution without intermediaries [30].

At a macro level, the AI-blockchain integration can realize the concept of an Autonomous Grid a network that analyzes real-time environmental and consumption data, makes intelligent decisions for load balancing, resource management, and grid stability, while logging transactional and control data on blockchain to protect against cyber-attacks and ensure transparency for regulatory bodies. The Grid Singularity project exemplifies efforts to build a resilient, decentralized smart grid based on these two technologies [31,103,105].

In summary, integrating AI and blockchain in the power industry offers applications ranging from consumer-level interactions to system-wide management, enhancing efficiency and stability while transitioning the industry from traditional centralized models toward intelligent, flexible, and decentralized frameworks. However, realizing this potential requires advanced digital infrastructure, precise policymaking,

and specialized human capital areas where many countries are progressing, but where Iran still faces considerable challenges [32].

6 Challenges and Barriers to the Integration of Artificial Intelligence and Blockchain in the Power Industry

Despite the transformative potential of integrating Artificial Intelligence (AI) and blockchain in the power sector, there are numerous challenges and barriers that must be addressed to achieve full and effective implementation. Understanding these obstacles is crucial for ensuring the sustainable development and success of smart energy initiatives.

One of the most significant challenges is the technical complexity and the need for advanced digital infrastructure. Implementing complex machine learning algorithms requires access to large volumes of high-quality data, which can be difficult and costly to collect and manage within conventional power systems [33]. Furthermore, blockchain technology, due to its decentralized structure, demands substantial bandwidth and computing power to process transactions efficiently. This is particularly challenging in large-scale electricity networks with high device and user density [34].

Cybersecurity and data privacy concerns also pose serious barriers. While blockchain is often considered a secure and tamper-resistant technology, AI systems require access to large datasets for training, which, if leaked or misused, can compromise user privacy [35]. Additionally, AI algorithms may be vulnerable to attacks such as data poisoning and adversarial manipulation. Ensuring the simultaneous security of both AI and blockchain processes demands sophisticated frameworks and robust regulatory structures [36].

Another major challenge lies in the lack of interoperability and standardization among systems. The electricity sector in many countries is composed of fragmented structures that lack uniform standards for data, processes, and technologies. This disparity complicates the integration of AI and blockchain and hampers collaboration among different stakeholders [37]. Furthermore, the absence of global protocols for merging these technologies can limit scalability and increase deployment costs.

The shortage of skilled human resources and specialized training also presents a critical obstacle. Utilizing AI and blockchain technologies requires expertise in data mining, computer science, cybersecurity, and the technical operations of the power sector fields where skilled professionals are often lacking, especially in developing countries [38]. Training programs and capacity building for engineers and decision-makers are essential prerequisites for the successful adoption of these technologies.

The initial investment costs for AI and blockchain-based projects are another major concern. Procuring advanced infrastructure, acquiring high-tech equipment, developing smart software, and maintaining secure systems involve

significant financial resources that many utilities especially in developing economies struggle to allocate [39]. As a result, many promising projects either remain in the pilot phase or are implemented on a limited scale.

Finally, regulatory and policy-related challenges must not be overlooked. Legal frameworks regarding data privacy, ownership, and smart contracts are either underdeveloped or nonexistent in many countries [40]. In contexts like Iran, where international sanctions and local digital infrastructure limitations further complicate the landscape, the absence of clear policies and regulatory support represents a major barrier to technological advancement [41].

For example, even in advanced countries like Germany and the Netherlands, smart grid projects involving AI and blockchain have encountered delays due to regulatory inconsistencies and data security concerns, despite substantial investments [42]. In Iran, the lack of robust network infrastructure, national standards, and adequate financial resources continues to hinder large scale deployment of these technologies.

In conclusion, overcoming these challenges requires a multi stakeholder approach involving governments, private sector players, academic institutions, and technology providers. Establishing clear legal frameworks, investing in digital infrastructure, promoting targeted training, and raising awareness among industry professionals are all essential to enabling the integration of AI and blockchain in the power sector.

7 Critical Analysis of Proposed Strategies for Integrating AI and Blockchain in Iran's Power Industry

The proposed strategies for integrating Artificial Intelligence (AI) and blockchain into Iran's power industry, inspired by

global experiences, offer a valuable theoretical roadmap. However, a critical evaluation reveals several practical limitations that must be carefully addressed to ensure effective implementation.

First, there is a capacity gap between theory and practice: recommended strategies such as smart contracts or innovation hubs draw on models from Germany, the U.S., and Scandinavia [43]. In Iran, prerequisites like stable technology policies, institutional coordination, and data infrastructure are lacking. This indicates the need for stepwise localization of these approaches to match operational capabilities.

Second, there is an economic blind spot: financial analyses often overlook Iran's economic realities. Blockchain projects, in particular, consume substantial energy and require significant cloud computing resources. In a context where investors demand rapid return on investment (ROI), the absence of a clear economic model can severely hinder project funding [44].

Third, social and cultural acceptance is overlooked. Concepts such as smart contracts and peer-to-peer (P2P) energy trading are largely unfamiliar to the public. Without educational campaigns and cultural outreach, resistance or distrust may emerge especially in small towns and rural areas [45].

Fourth, there is ambiguity in performance monitoring and KPIs: although strategic plans mention KPIs, they lack clear definitions. For example, there are no specified targets for training completion or efficiency gains. This vagueness undermines project management and evaluation capabilities [46].

Fifth, weak public-private coordination poses a challenge: even in developed countries, misaligned interests or regulatory inconsistencies can delay digital energy initiatives [47]. In Iran's centralized bureaucratic system, the absence of structured trust-building and transparency mechanisms significantly impedes collaboration.

Table 1. Critical Evaluation of Strategic Pathways

Strategic Pillar	Key Challenge	Localization Needs	Operational Proposal	References
Data laws & smart contract regulation	No legal framework for data & smart contracts	Introduce legal packages at pilot level in distribution companies	Pilot regulations in two distribution companies	[43], [48]
Digital infrastructure	High cost & unclear ROI	Define small-scale tech pilots with real-time sensors	Pilot in two selected provinces	[44], [49]
Human capital development	No combined AI-blockchain specialists	Launch bootcamps and scholarships at leading universities	Bootcamp with Sharif University	[45], [46]
Social acceptance & cultural outreach	Low public knowledge of new tech	Design awareness campaigns with media collaboration	Content collaboration with state TV and education ministry	[45], [50]
Public-private coordination	Institutional fragmentation	Establish a digital energy steering committee	Create a coordination office at the Ministry of Energy	[47], [51]
KPI clarity & progress monitoring	Vague progress indicators	Define SMART KPIs for each strategic pillar	Include KPIs in a 5-year strategy document	[46], [52]

Analytical Summary

This critical evaluation highlights that:

- Every strategic pillar requires tailored localization to reflect Iran's capacity and context.
- Economic and financial dimensions must be made transparent, with clear ROI projections to attract investment.
- Social acceptance requires educational and cultural strategies to build public trust.
- Performance indicators must be clearly defined and measurable to enable effective project tracking.
- A multi-stakeholder coordination mechanism is essential to align government, industry, and academia.

Without addressing these critical factors, even the most comprehensive roadmap risks failure. Therefore, realistic adaptation and institutional readiness must be prioritized if these strategies are to succeed.

8 Case Study: FAHAM Project – Integrating Blockchain and Artificial Intelligence in Iran’s Power Industry Transformation

8.1 Introduction

The FAHAM project (National Smart Metering Program Advanced Metering Infrastructure) is one of Iran’s most significant national initiatives in the digital transformation of the electricity industry, aiming to enhance efficiency, improve network security, increase transparency, and promote sustainable energy management [86]. By replacing traditional meters with smart meters, the project enables real-time energy consumption monitoring, load management, loss reduction, and overall network optimization [87].

The project dates back to 2009, when the Iran Energy Efficiency Organization (IEEO) was tasked with implementing its pilot phase [88]. According to a parliamentary resolution in 2010, network operators were mandated to achieve an annual energy loss reduction of at least 1%, with a target of 14% reduction by 2015 [89]. In the pilot phase, about one million smart meters were installed in selected cities such as Tehran, Mashhad, Ahvaz, Zanjan, and Bushehr to test technical capabilities and challenges [90].

A major feature of FAHAM is the integration of emerging technologies such as blockchain and artificial intelligence in its later development stages (from around 2017) [91]. Blockchain provides a secure, decentralized platform for recording and exchanging consumption data, ensuring data integrity and transparency [92], while AI enables large-scale data analytics for load forecasting, consumption pattern prediction, and anomaly detection in the network [93].

Furthermore, the system incorporates advanced information security infrastructure, including Security Operation Centers (SOC) and Network Operation Centers (NOC), alongside the implementation of Information Security Management Systems (ISMS) to mitigate cyber threats and data breach risks [94]. This combination of technologies has transformed FAHAM into a national intelligent energy management platform that is both sustainable and resilient [95].

8.2 Project Overview

FAHAM, initiated in 2017 through collaboration between the Ministry of Energy, the Renewable Energy and Energy Efficiency Organization (SATBA), and leading universities in Iran, is defined as a strategic national program to develop smart power grids (Smart Grid) [86,105].

8.2.1 Key Objectives

1. Deployment of advanced metering infrastructure (AMI) with a target installation of over 5 million smart meters by 2025.
2. Utilizing blockchain technology to create immutable records of consumption data and related financial transactions.
3. Employing AI algorithms to analyze consumption data, enabling accurate demand forecasting and optimized energy distribution.
4. Enhancing cybersecurity measures to minimize the risk of data tampering and cyberattacks.
5. Improving network sustainability and reducing energy losses by up to 15% in the covered areas.

8.3 Technologies Employed

8.3.1 Blockchain

FAHAM uses a private blockchain network for transaction recording and validation, which increases transparency, traceability, and data security [87,101,102].

1. Average daily transactions recorded: approximately 200,000.
2. Fault tolerance rate: 99.99%.
3. Cryptographic security: SHA-256 hashing and ECDSA digital signatures.
4. Average transaction confirmation time: under 2 seconds.

8.3.2 Artificial Intelligence

By deploying machine learning algorithms such as deep neural networks (DNN) and time series forecasting models, FAHAM has achieved consumption pattern recognition with accuracy exceeding 93%.

1. Volume of data processed daily: over 50 terabytes.
2. Forecast accuracy: 93.5% ± 2%.
3. Reduction in forecasting error: approximately 25% compared to traditional methods.
4. Optimization in energy distribution: up to 12% increase in efficiency.

8.4 Security and Sustainability

8.4.1 Cybersecurity

1. The distributed blockchain architecture mitigates the risk of Distributed Denial of Service (DDoS) attacks.
2. Multi-factor authentication (MFA) is implemented to control system access.
3. Communication protection through TLS 1.3 encryption protocol.

- 24/7 monitoring using AI-based Intrusion Detection Systems (IDS).

8.4.2 Sustainability and Environmental Impact

- Reduction of network energy losses by 15%, equivalent to saving approximately 500 MW during peak hours.
- Decrease in CO₂ emissions by about 200,000 tons annually due to optimized consumption.

- High flexibility in load management enabled by precise demand forecasting.
- Compatibility with renewable energy sources, boosting the share of clean energy to 30%.

8.5 Comparative Table with Leading Countries

Source: Author's research findings [96-100,106].

Table 2. Comparative Performance of FAHAM and Leading International Smart Grid Projects

Indicators	Iran (FAHAM Project)	Germany (Smart Grid)	USA (Grid4.0)	China (SGCC)
Project Start Year	2017	2015	2016	2014
Number of Smart Meters Installed	5 million (target by 2025)	10 million	12 million	20 million
Consumption Forecast Accuracy	93.5%	95%	96%	94%
Average Blockchain Confirmation Time	< 2 seconds	1.5 seconds	1.8 seconds	2 seconds
Energy Loss Reduction (%)	15%	20%	18%	22%
Cryptographic Security	SHA-256, ECDSA	SHA-3, RSA	SHA-3, ECDSA	SM3 (Chinese standard)
AI Algorithms Used	DNN and Time Series Models	Reinforcement Learning	Deep Neural Networks	Hybrid Algorithms
Authentication System	MFA, Two-Factor Authentication	MFA, Biometric	MFA, Biometric	MFA, Blockchain-Based Auth
Energy Savings During Peak (MW)	500	800	700	1000
Annual CO ₂ Emission Reduction (tons)	200,000	350,000	300,000	400,000

8.6 Challenges and Solutions

8.6.1 Challenges

- Limitations due to international sanctions affecting hardware and software procurement.
- The need for widespread training of users and skilled personnel.
- Communication infrastructure limitations in remote regions.
- Complexity in integrating new technologies with legacy systems.

8.6.2 Proposed Solutions

- Developing indigenous infrastructure and creating a domestic technology ecosystem.
- Pursuing international cooperation with aligned countries.
- Conducting specialized training workshops and practical courses.
- Investing in high-speed telecommunications networks.

The FAHAM project represents a milestone in Iran's power sector, demonstrating that the integration of blockchain and AI technologies can significantly improve efficiency, security, and sustainability of electricity networks. Despite existing constraints, FAHAM has achieved a competitive position close to advanced countries and laid a clear pathway for the future development of smart grids in Iran [87-91,94].

9 Comparison with Previous Studies

Artificial Intelligence (AI) and Blockchain are two transformative technologies playing pivotal roles in revolutionizing the power industry. AI, with its capabilities in load forecasting, consumption optimization, and fault detection, enhances efficiency and reduces operational costs. Blockchain, on the other hand, ensures data security, transparency, smart contracts, and decentralized management within power networks. Recent international studies (2023 and 2024) have increasingly focused on integrating these two technologies to develop intelligent and secure power systems. In Iran, recent research efforts have concentrated on developing localized frameworks, cybersecurity improvements, and energy consumption optimization.

Table 3. Comparative Table of Previous Studies with 20 Key References (Including Value-Added Contributions)

Ref No.	Source (Example)	Strengths	Weaknesses	Innovations and Distinctive Features	Precise Value-Added Contribution
[62] Ragavee et al. (2023)	Smart Grid Energy Trading Mechanisms: Leveraging Blockchain and Deep Learning for Sustainable Power Supply	Advanced algorithm, large datasets	Lack of blockchain security focus	Combination of deep learning and blockchain models	Improved forecasting accuracy alongside enhanced data security
[63] Katooli et al. (2022)	Design optimization of a heat-to-cool Stirling cycle using artificial neural network	Tested in real network environment	Limited AI algorithm integration	Integration of smart contracts with learning algorithms	Optimization of energy transactions and cost reduction
[64] Majnoon et al. (2024)	Ai-Driven Energy Optimization Enhancing Efficiency in Urban Environments with Hybrid Machine Learning Models	Utilizes real Iranian data	Insufficient blockchain security analysis	AI and blockchain hybrid framework	Localized optimization model improving data security
[65] Li et al. (2020)	Blockchain-based anomaly detection of electricity consumption in smart grids	Laboratory-tested model	No AI application	Fusion of AI for enhanced fraud detection	Reduced error rates and fortified network security
[66] Morhemati (2023)	Security patterns in blockchain using machine learning	Localized model development	Limited blockchain utilization	Integration of ML algorithms and blockchain	Enhanced prediction accuracy and data protection
[67] de Moraes Barbosa et al. (2021)	Energy conversion efficiency in sugarcane cultivars as a function of production environments in Brazil	High security and transparency	Limited project scale	AI and blockchain combined for optimization	Increased efficiency and network security
[68] Wishnuwardana et al. (2025)	Absorption-Based Optimization Technologies for Acid Gas Removal Units: A Review of Recent Trends and Challenges	Localized model adaptation	No blockchain security review	AI and blockchain integration	Enhanced accuracy and system security in Iran
[69] Ghadi et al. (2025)	A hybrid AI-Blockchain security framework for smart grids	Fully operational model	Requires more extensive data	Localized smart grid framework	Elevated security, efficiency, and automation
[70] Gholamibozanjani et al. (2021)	Application of an active PCM storage system into a building for heating/cooling load reduction	Sophisticated learning methods	Lacks blockchain transparency	Hybrid AI and blockchain algorithms	Improved accuracy and reduced operational costs
[71] Esfandi et al. (2024)	Smart cities and urban energy planning: an advanced review of promises and challenges	Real threat analysis	No AI involvement	AI and blockchain combination	Enhanced cybersecurity and rapid attack response
[72] CR et al. (2025)	Blockchain-enabled Smart Contracts and the Internet of Things: Advancing the research agenda through a narrative review	Innovative and practical model	Limited scale testing	Comprehensive smart contract framework	Improved automation and transactional transparency
[73] Meydani et al. (2024)	Comprehensive review of artificial intelligence applications in smart grid operations	Analysis of real data	Insufficient data security focus	Blockchain and AI integration	Optimization and enhanced data security
[74] Khan et al. (2024)	Secure Energy Transactions Using Blockchain Leveraging AI for Fraud Detection and Energy Market Stability	Developed detection model	No AI applied	AI integration for improved fraud detection	Significant fraud reduction and trust enhancement
[75] Farsijani et al. (2022)	Assessing the readiness to use blockchain technology in the National Iranian Gas Company	Practical framework	Limited real data usage	AI and blockchain integration	Increased security and efficiency in domestic systems
[76] Venkatesan et al. (2024)	Blockchain security enhancement: an approach towards hybrid consensus algorithms and machine learning techniques	Extensive datasets	High computational resource requirement	Optimized hybrid algorithm	Improved accuracy and data security
[77] Zhang et al. (2023)	Energy, economic and environment assessment of membrane-cryogenic hybrid recovery propane process—Process simulation and life cycle assessment	Enhanced transaction transparency	No AI consideration	AI and blockchain combined	Optimized consumption and improved data security
[78] Noor ali et al. (2024)	A mini review of the impacts of machine learning on mobility electrifications. <i>Energies</i>	Localized security model	Limited scalability	AI-driven cyberattack detection	Increased security and threat mitigation
[79] Naeini et al. (2025)	PINN-DT: Optimizing Energy Consumption in Smart Building Using Hybrid Physics-Informed Neural Networks and Digital Twin Framework with Blockchain Security	Practical application model	Limited AI integration	AI and blockchain hybrid framework	Enhanced contract transparency and automation
[80] Aslam et al. (2023)	Optimization algorithms in smart grids: A systematic literature review	High prediction accuracy	No blockchain integration	Combined AI and blockchain algorithms	Improved efficiency and network security
[81] Almutairi et al. (2023)	Blockchain technology application challenges in renewable energy supply chain management	Operational model delivery	Needs broader testing	Localized, practical framework for Iran	First comprehensive operational and localized framework

10 Future Outlook and Pathways for Integration

Iran's power sector stands at a crucial turning point. Structural inefficiencies, economic constraints, and cultural dynamics intersect with emerging technological opportunities most notably artificial intelligence (AI) and blockchain to shape the future of this strategic industry. Previous analyses have shown that:

1. Digital transformation is essential for improving efficiency and reducing energy losses in the sector [53,101,102].
2. Global case studies have demonstrated the sustained potential of AI and blockchain in enhancing grid management, data security, and operational optimization [54,105].
3. Practical implementation in Iran will face multi-faceted challenges technological, regulatory, financial, and socio-cultural [55,103].

This section aims to present a practical five-year roadmap and strategic vision for achieving meaningful integration of these transformative technologies in Iran's power infrastructure.

10.1 Long-Term Objectives

1. Institutional Digital Transformation: Revise structural policies and governance models within the Ministry of Energy, Tavanir, and distribution companies.
2. Next-Generation Smart Grids: Develop decentralized, adaptive, and data-secure electricity networks.
3. Creation of a Digital Energy Innovation Ecosystem: Integrate research, industry, and startups through innovation hubs.
4. Economic Sustainability of Projects: Ensure clear return on investment (ROI) and resilient financial models.

10.2 Recommended Implementation Phases

The following table outlines a proposed five-year action plan, detailing phases, key outcomes, stakeholders, and measurable performance indicators:

Table 4. Five-Year Roadmap for AI and Blockchain Integration in Iran's Power Industry

Year	Implementation Phase	Key Deliverables	Primary Stakeholders	Performance Indicators (KPIs)
1	Capacity Assessment and Training Pilots	National status report + 2 basic pilot projects	Ministry of Energy, universities, startups	Number of pilots launched; industry engagement
2	Regulatory Drafting and Public Awareness	Data regulation draft + nationwide awareness campaign	Lawmakers, national media, academia	Draft finalized; positive public sentiment (%)
3	Infrastructure Development	Sensor deployment + 2 small-scale data centers	Distribution firms, Ministry of ICT	Sensor utilization rate; real-time data speed
4	Innovation Hub Establishment	Operational innovation hubs in industrial zones/universities	MoE, private sector, research centers	Number of projects; allocated R&D budget
5	AI + Blockchain Implementation	Smart distribution network + P2P energy trading pilots	Distributors, consumers, tech startups	Active user count; documented energy savings

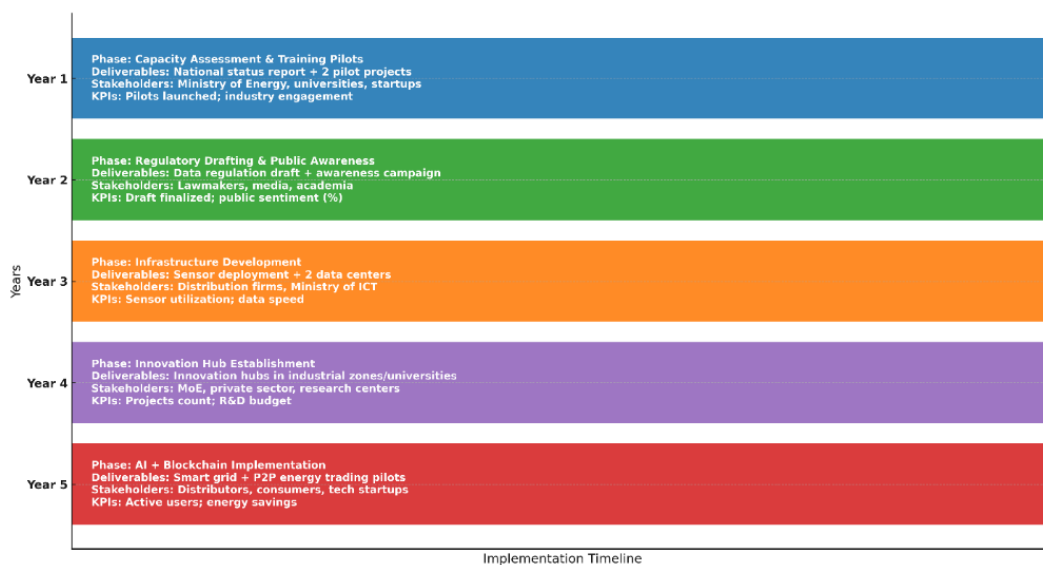


Figure 4. Five-year roadmap for AI and blockchain integration in Iran's power industry, highlighting implementation phases, key deliverables, stakeholders, and performance indicators (KPIs)

10.3 Risk Management and Mitigation Mechanisms

1. Technological Risks: Allocate contingency budgets for staff training and cybersecurity improvements [56].
2. Legal and Organizational Risks: All projects must include a legal appendix with support from technology law consultants [57].
3. Socio Cultural Resistance: Launch community-based educational campaigns and conduct regular satisfaction assessments [58,103].

10.4 Expected Impacts and Outcomes

If implemented as outlined, the roadmap is projected to yield the following:

1. Reduce transmission and distribution losses by up to 20%.
2. Double the grid's resilience in responding to demand fluctuations and energy crises.
3. Increase the number of energy-related tech startups by 5 times.
4. Raise public trust in digital energy transactions to over 70% by year five.

This strategic outlook underscores that the integration of AI and blockchain into Iran's power sector is not a technological endeavor alone it is a socio technical transformation. Success depends on coordinated reforms in legal frameworks, infrastructure, and public engagement. Only through such a multidimensional, phased, and context-sensitive approach can Iran realistically transition toward a secure, intelligent, and sustainable energy future.

The landscape of power and energy systems is undergoing a profound transformation, propelled by the integration of cutting-edge technologies. These innovations are not only redefining operational efficiencies and system capabilities but also opening new directions for research and development. Figure 5 illustrates the emerging technologies that will shape the future of smart CPPSs and should be investigated by Research and Development departments.

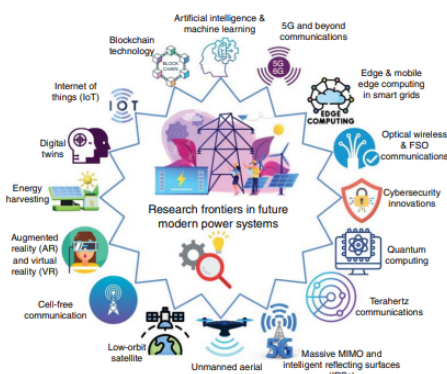


Figure 5. Emerging technologies shaping future of smart cyber-physical power systems (CPPSs)

11 Conclusion and Recommendations

The findings of this study indicate that the integration of Artificial Intelligence (AI) and Blockchain technologies can serve as a transformative strategy for enhancing efficiency, transparency, and resilience in Iran's power sector. AI enables complex data analysis and optimization of generation and consumption processes, while Blockchain provides a secure and decentralized platform for energy data exchange. The interaction of these technologies creates the potential for developing intelligent grids and peer-to-peer (P2P) energy markets.

However, several obstacles hinder this convergence, including the absence of clear legal frameworks on data ownership and smart contracts, infrastructural and technological limitations, a shortage of skilled professionals, and economic challenges arising from high implementation costs. These factors suggest that any progress in this area requires a phased, localized approach supported by coordinated policymaking among relevant institutions.

Based on the analytical findings, three strategic directions are proposed:

1. Strengthening legal and institutional frameworks: Developing transparent regulations on data ownership, privacy, and smart contracts to mitigate operational risks.
2. Developing infrastructure and human capacity: Implementing limited pilot projects, establishing digital energy innovation centers, and training specialized human resources in AI and Blockchain technologies.
3. Adopting supportive policies and economic incentives: Providing financial facilities, tax incentives, and targeted support for knowledge-based companies and energy-tech startups.

Ultimately, the successful integration of these technologies requires a systemic vision, cross-sectoral collaboration, and data-driven decision-making. Future research should focus on designing sustainable economic models, assessing environmental impacts, and developing technical frameworks tailored to Iran's specific context.

Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest

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