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A Comprehensive Hierarchical Review of Blockchain Technology in Revolutionizing Carbon Emission Trading System

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Attestation

We are aware of the fact that plagiarism is strictly prohibited and it conflicts with our university's rules and regulations. We guarantee the authenticity of our work. We have used some copyrighted material and models of others in our project, which has been properly cited following the international standards and proper guidelines.

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Acknowledgement

We would like to express sincere gratitude to our respected faculty, Sanzar Adnan Alam, Senior Lecturer, Department of Computer Science and Engineering, Independent University, Bangladesh. His dedicated guidance, insightful suggestions, remarkable patience, and generous investment of his valuable time played a pivotal role in the successful completion of our project. Our Professor's expertise and mentorship greatly enhanced the quality and depth of our work, and we are truly appreciative of his unwavering support throughout our academic journey.

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Letter of Transmittal

Nayeem Khan
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23 August 2025

To
Sanzar Adnan Alam
Lecturer A, Department of Computer Science and Engineering
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Subject: Submission of Final Undergraduate Thesis

Dear Sir,

I am pleased to submit my undergraduate thesis titled “A Comprehensive Hierarchical Review of Blockchain Technology in Revolutionizing Carbon Emission Trading System”, submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Computer Science & Engineering.

This research, conducted under your supervision, explores the integration of blockchain, artificial intelligence, and IoT within the proposed BAIC-Gov framework to enhance transparency, automation, and fraud prevention in carbon emission trading systems. The study critically reviews existing approaches and demonstrates how BAIC-Gov can address inefficiencies in current carbon markets, while aligning with global sustainability goals.

I would like to express my sincere gratitude for your valuable guidance, encouragement, and support throughout the research process.

Thank you for your time and consideration.

Sincerely,
Nayeem Khan
2120756
On behalf of Group SAA-G04

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Abstract

The growing climate crisis has raised the need to search for reliable mechanisms which could reduce greenhouse gas gas emissions worldwide. Carbon markets can continue to play a central role in this effort but often there is a problem of duplication of credit, fraud, multi-jurisdiction and poor traceability. There is an attempt to avoid such shortcomings by suggesting a multi-layered framework, called BAIC-Gov. The framework enables automated and verifiable monitoring and enforcement of carbon credits through blockchain technology, smart contracts, live real-time data on the Internet of Things (IoT) and anomaly detection via Artificial Intelligence (AI). Smart contracts are coded in such a way that they will be directly connected to the emissions data measured by IoT sensors, thus credit issuance as well as compliance will take place autonomously and with precision. Such application was illustrated with the use of the IBM-China ETS and Toucan Protocol. The framework enhances the climate governance, the ability of the market to scale, and the willingness by countries around the world to achieve carbon neutrality to establish a more sustainable future by strengthening confidence and integrity in carbon trading.

Keywords-Blockchain, Emission Trading System (ETS), Smart Contracts, Internet of Things (IoT), Artificial Intelligence (AI), Anomaly Detection, Carbon Credit Tokenization, Sustain ability, Decentralized Finance (DeFi).

Contents

List of Tables

List of Figures

1 Introduction

1.1 Background and Motivation

Climate change has emerged as one of the most pressing global concerns, with far-reaching environmental, social, and economic consequences. Rising temperatures, extreme weather events, and ecological degradation have forced governments, organizations, and communities to search for sustainable solutions. Among these, carbon markets and emission trading systems have become key policy instruments to incentivize emission reduction in a cost-efficient manner.

1.1.1 Climate Change and the Role of Carbon Markets

The issue of climate change stands alone as the most urgent challenge of the 21st century where the global community must take stringent measures and initiative to alleviate anthropogenic greenhouse gas (GHG) emissions [1],[2]. Most mitigation strategies have followed different approaches such as the Emission Trading Systems (ETS) which have furnished a market based approach of reducing carbon emissions in a cost effective way. ETS is designed in such a way that emitting permits are assigned to the participants, and they could either trade the excess credits or buy more to ensure conformity to the permit[18], [19]. Nevertheless, amid the extensive use of the traditional ETS models, they still experience major challenges that border on duplication of credit, fraudulent transactions, fragmented regulatory status, and overall lack of transparency[3] [5]. These problems deteriorate the level of trust in the market, consumption pace, and the worldwide movement towards carbon neutrality. Enforcing transparency, traceability and automation in ETS is, thus, quintessential in having scale and verifiable climate action.

1.1.2 Blockchain Technology in Carbon Governance

This decentralized ledger can be viewed as a shared environment, which is immutable, and may help resolve most of the inefficiencies of the existing ETS systems[6] [7]. Blockchain provides traceability and limits dependency of the central authority because of recording transactions in networks that are distributed and tamper proof. The programmable legal framework, or brainchild of smart contracts-automated agreements operating on blockchain platforms, can facilitate the issuance, retirement, and compliance confirmation in a carbon credit market when the administrative overhead and human error are reduced to a bare minimum[5],[16] .

Blockchain based ETS is capable of providing end to end transparency, detection of fraud in transactions, and adaptive mechanisms of compliance in case of integration with real time data of IoT sensors analyzed by AI algorithms[3] [9]. Blockchain in climate governance is also environmentally viable through the establishment of sustainable consensus mechanisms such as Proof of Stake (PoS) or Delegated Proof of Stake (DPoS)[22].

1.1.3 The BAIC-Gov Framework

One example suggested in Blockchain AI IoT Carbon Governance (BAIC-Gov) framework is a blockchain-based layered architecture that incorporates layers built on blockchain infrastructure, AI facilitated anomaly detection, and IoT based emissions detection[8],[10]. The suggested BAIC-Gov format is organized in four coordinated levels so that it is smooth, transparent as well as reliable with respect to carbon emission trading systems. Layer 1 uses an energy efficient blockchain infrastructure to give immutable record keeping and secure management of tokenized carbon credits. Through this layer, all the transactions that are made become tamper proof and traceable, which provides the basis of having an operation of trust in the market. Layer 2 incorporates smart agreements to automate compliance efforts and a full-fledged lifecycle of carbon credits, such as issuance, transfer, and retirement that help minimize administration costs and related human error. Layer 3 takes advantage of AI powered fraud detection systems, through weighted anomaly scoring to empower real time detection of anomalies in trading activities and emission data reporting[3] [9]. Layer 4 integrates IoT enabled data capture to maintain continuous emissions monitoring, and automated data check to provide validity of data to the integrity and accuracy of the environmental measurement [17]. These layers, combined, form a robust, independent and scalable next generation governance of carbon markets.

BAIC-Gov negates copain And addresses both compliance and voluntary carbon markets via cross border credit trade, auditability and creates trust due to transparent and verifiable processes.

1.1.4 Integration of IoT in Emissions Monitoring

The IoT devices are central enablers of real time and verifying monitoring of emissions. The greenhouse gas data monitored by sensors set on the emission sources may be continuously collected and transmitted to the blockchain through simple communication standards, LoRaWAN, NB-IoT, or 5G [17]. This data, authenticated using Public Key Infrastructure (PKI) is used to measure the integrity and stop tampering.

Such automatic data reception can drastically lessen the reporting required by hand, raise the level of confidence on the values reported and allow immediate issue of carbon credits on the measured emissions.

1.1.5 Artificial Intelligence in Carbon Market Compliance

AI completes carbon governance enabling real time analytics and anomalous detection[3] [9]. Applying variables like the frequency of transactions, size of trade, and something out of the norms of the past, AI models can signal suspicious behavior and initiate automated actions within smart contracts. Due to the severity of deviations, weighted systems of anomaly scoring allow quantifying the severity of deviations in an accurate, scalable manner to detect fraud. Additionally, privacy preserving AI tools like zero-knowledge machine learning (zkML) will guarantee that any kind of sensitive data can be proven without revealing proprietary or confidential information .[22]

1.1.6 Importance of a Tokenized Carbon Lifecycle

Carbon credit tokenization makes it possible to standardize, transparently, and access tradable digital assets in blockchain platforms. The protocols like ERC 1155 or ERC 3643 allow creating each credit with the metadata about its origin, compliance history, and ownership history[14], [15]. This 'normalised tokenised representation' between expiry, trading, staking in DeFi or retirement creates complete traceability, facilitates secondary markets (including retirement) and increased participation in carbon offset schemes.

1.2 Problem Statement

Climate change mitigation has necessitated adopting Emission Trading Systems (ETS) as a market based forum in reduction of greenhouse gases emissions across the world [1], [2]. Although ETS has a consistent and flexible mechanism to encourage emission cut, there are some substantial operational issues towards its current applications, such as duplication of credits, opacity, fraud, and administrative dispersity [3],[4]. All these faults negate market credibility, pernicious adoption processes, and reduce the potential of ETS in delivering substantial value to the global climate goals [5].

On the ground, the ETS platforms based on centralized registries and labor intensive verifications are in fact not only time consuming in nature, but also error prone and subject to manipulation[6] [7]. There is a verification delay because of not having realtime monitoring, and crossjurisdiction inconsistency without interoperability and standardization between national or regional carbon markets [2], [8]. Additionally, automated compliance systems are practically nonexistent (with the regulators relying on after the fact checks as opposed to the proactive enforcement)[9],[10].

Such shortcomings are especially of concern with regard to scaling of carbon markets in accordance with the requirements of a rapidly expanding global carbon economy. The larger the volume of trading and the number of jurisdictions in which ETS schemes are implemented, the more inefficient processes of credits monitoring, verification, and fraud detection will appear, preconditioning the systemic risk and decreasing the number of perceived trust between participants[11], [12].

Although new blockchain based ETS technologies including IBM China ETS, and Toucan Protocol provide better transparency, traceability, and credit tokenization, they are extremely far behind in terms of offering fully integrated, real time compliance monitoring using IoT devices and AI based anomaly detection [12], [13]. There is also a shortage of universal tokenization protocols and secure cross platform integration that still has its impact on the worldwide adoption and interoperability [14] , [15].

It is necessary to overcome these issues with a versatile, technologically sophisticated model capable of integrating decentralized ledger technology, real time environmental data acquisition and smart compliance systems. The suggested BAIC-Gov (Blockchain AI-IoT Carbon Governance) framework also works to eliminate such gaps by providing automated, verifiable, and fraud resistant carbon trading mechanisms and the scheme complies with both types of market: voluntary and compliance. BAIC-Gov offers the potential of improving market integrity, scalability and cross border compatibility, through blockchain-based immutable record keeping, IoT-based and real-time continuous emissions monitoring, and AI-based adaptive fraud detection [3], [8], [17].

1.3 Ethical Consideration

The study that was done in this present paper followed the ethical standards and was formally approved by the Institutional Review Board (IRB) of our university (Reference: 2025 BAIC-GOV ETS. The publicly accessible data of all the sources were non-identifiable and were collected using data of publicly available materials (open access ETS records, block chain transaction logs, and technical documentation of the existing carbon trading platforms).

There was not any active human participation in the main data collection process. In terms of expert interviews to check the BAIC-Gov framework design, the participants were contacted through email, informed about the objectives of the research, and requested to accept an informed consent before their involvement. The consent was done electronically in that a participant was asked to agree to the start of any interview.

All the data obtained was secured and used only to carry out the research work. All the possibly sensitive information conveyed during the interviews was anonymized to ascertain confidentiality. There was no leakage of personal or proprietary information and data was reported in aggregate to respect participant privacy and stand up to data protection laws.

1.4 Research Gap

Although blockchain technology is used to promote transparency, traceability, and automation in different fields, its application in the framework of Emission Trading Systems (ETS) is still quite inconsistent and concise. Possible improvements in credit tokenization and transactions transparency as well as partial automation have been presented by current implementations, like the IBM China ETS and Toucan Protocol. Some of these solutions, nevertheless, are not yet integrated on a full scale with Internet of Things (IoT) enabled real time emissions monitoring and Artificial Intelligence (AI)-enhanced anomaly detection [8], [12], [13]. This lack of automation, verifiability and vulnerability management to fraud constrains the prospects of internationalization and reputability to carbon markets.

There is yet another hole in cross platform interoperability. The existing blockchain -based ETS schemes are usually deployed in closed networks, where there are no harmonized tokenization processes or compliance matching solutions enabling credits to be accepted across boundaries [2], [14] , [15]. As carbon markets continue to become more global, the heterogeneity of cross-platform transfer and verification of credits, and retirement thereof present a high risk that markets cannot fully embrace.

Furthermore, although existing research considers blockchain to be used in sustainability, there is little research depicting a modular and layered architecture that integrates blockchain infrastructure, smart contract automation, AI driven fraud detection, and IoT based emissions tracking into a unified governance architecture. BAIC-Gov addresses this gap through provision of an integrated system which can be end end automatable, vertically integrated with real time verification and regulatory acceptability, serving the voluntary and compliance carbon markets.

1.5 Research Objectives and Research Questions

1.5.1 Research Objectives

With this study, it is possible to create and test the Blockchain-AI-IoT Carbon Governance (BAIC Gov) system that will offer the solution to such inefficiencies, fraud risks, and verification challenges that the current carbon market structures have to face, trading them off the global markets. Some of the problems currently encountered with existing Emission Trading System (ETS) platforms include inadequate delay in verification, vulnerability to fraudulent reporting, a deficit in jurisdiction-level interoperability, and poor credit lifecycle monitoring transparency. In a bid to curb the challenges, the suggested BAIC-Gov solution incorporates blockchain technology to maintain immutable records, tokenized carbon credit management, IoT systems to continuously monitor emissions in the real time environment, and AI to have score-weighted anomalies and intelligent fraud detection. The research problems attempt to achieve four goals, which include the following: the first goal is to develop an in-depth evaluation of current ETS implementations to outline key shortcomings and delineate the technological gaps; the second goal is to design and implement a multi layered BAIC-Gov architecture that may be used to manage carbon credits in a secure, automated, and transparent manner; the third goal is to prove the validity and scalability of a proposed framework on the basis of comparative case studies involving IBM China ETS, Toucan Protocol, and ClimateTrade; and the fourth is A combination of these goals seeks to present a strong, future proof governance system that may work to achieve global carbon neutrality ambitions and promote confidence, productivity, and innovation in carbon trading environment.

1.5.2 Research Questions

The study is structured around three central research questions (RQs):

RQ1: What design elements and technologies should be incorporated into a blockchain based ETS to enable secure, automated, and transparent carbon credit trading?

Rationale: To identify the essential components (blockchain protocols, IoT communication methods, AI models) required for a comprehensive governance framework.

RQ2: How can AI and IoT be integrated into blockchain based ETS platforms to enable real time emissions monitoring and fraud detection?

Rationale: To determine the feasibility, technical requirements, and operational workflows for achieving automated compliance and anomaly detection.

RQ3: In what ways does the BAIC-Gov framework improve scalability, interoperability, and trust compared to existing ETS implementations?

Rationale: To evaluate BAIC-Gov's advantages over traditional and partially blockchain enabled ETS platforms, using comparative analysis with real-world systems.

1.6 Research Outcome

The study led to the design and testing of BAIC-Gov, a tiered carbon governance system that combines blockchain to allow decentralized and tamper-proof record-keeping, IoT to securely and in real-time collect data about the environment, and AI to detect fraud through weighted anomaly scoring.

By comparing it to the available ETS implementations, the study shows that BAIC-Gov does not have a problem with double counting or fraudulent transactions due to the immutable trails in the record keeping. Facilitates the issuance (and retirement) of carbon credits automatically as verified emissions data by IoT. Facilitates cross border trade by establishing uniform token protocols which contain compliance metadata. Enables greater scalability through a modular hook to permissioned and open blockchains. In the future, the BAIC-Gov structure is going to evolve to encompass post quantum encryption to provide long term protection, cross chain interoperability standards to be adopted worldwide and state-of-the-art AI models to allow predictive compliance checks.

1.7 Report Outline

Chapter 1 (Introduction):
The chapter presents to readers the global climate crisis and why there is an urgent necessity to have sound mechanisms to curb the emission of greenhouse gasses. It puts into focus the role of emission trading. In climate governance as well as criteria of limitation of the existing system, such as inefficiencies, risks of fraud, and lack of coherence in regulations. The preface details the rationale behind the development of the Blockchain-AI-IoT Carbon Governance (BAIC-Gov) framework, the problem statement, ethical considerations, the identified research gaps, the research objectives, and the research questions that are considered when undertaking this research.

Chapter 2 (Fundamentals of Carbon Emission Trading Systems):
The chapter presents a summary of the theories of ETS as regards the cap and trade approach and the processes involved in the operationalization. It compares traditional ETS models with blockchain enabled ETS models and makes a point in associating how decentralization transforms the monitoring and compliance dynamics. The main problems of the duplication of credit, the frauds in transactions, inconsistencies across regulated jurisdictions, and the lack of transparency are explained to set up the baseline problems that BAIC-Gov intends to solve.

Chapter 3 (Overview of Blockchain Technology and Proposed Framework):
The essence of the main concepts behind the blockchain technology is outlined in this chapter, consisting of consensus mechanisms, distributed ledgers and the functional role of smart contracts. It presents the BAIC-Gov layered architecture, where it has explained the four layers of its energy efficient blockchain infrastructure, smart contract automation, AI based fraud detection, and IoT based data capture. There is also an extensive description of token lifecycle management protocols, workflow processes, and tech mapping of how to integrate IoT and smart contract logic..

Chapter 4 (Hierarchical Review of Blockchain Applications in ETS):
This chapter will be developed as a structured review of the blockchain applications to ETS and their capacity to solve the current challenges on the basis of decentralization, transparency, and

automation. It covers combining both blockchain and IoT to provide continuous monitoring, AI to detect anomalies such as malfunctions, and a decentralized finance (DeFi) system to enable trade in carbon credits on a transaction scale. The review has been arranged in a hierarchical order to demonstrate the contributions of the various technological elements making the processes of ETS efficiently run and trustworthy.

Chapter 5 (Case Studies and Real World Implementations):
This chapter looks at the three major real ETS implementations such as the IBM-China ETS, Toucan Protocol, and ClimateTrade. Operational model, technology stack, and the governance mechanisms are assessed in each case. These uses are cross-referenced with the BAIC-Gov layered architecture with the purpose to reveal the current strengths available, those that could be beneficial to integrate and enhance.

Chapter 6 (Challenges and Future Research Directions):
This chapter covers the technical implementation challenges like a shortage of standard tokenization procedures, procedural issues of domination among jurisdictions, sizing, and the maturing necessity of post quantum cryptographical safety. The possible solutions are suggested, including sidechains, sharding, rollups and the creation of global interoperability standards. Research directions are proposed to inform the further innovation in blockchain based carbon governance.

Chapter 7 (Conclusion and Future Work):
The chapter accumulates the main results of the study and confirms the applicability of the BAIC-Gov framework as a secure, transparent, and scalable opportunity to modernize the ETS. It points out contributions of the framework to carbon credit lifecycle automation, deterring fraud, and cross platform interoperability. Lastly it suggests future activities on areas of technical refinement, feedback of regulatory systems to international systems, and routes of global implementation.

2 Literature Review

This chapter will aim at providing a systematized overview of the current status of literature on the combination of blockchain, smart contracts, Internet of Things (IoT), and Artificial Intelligence (AI) in the Emission Trading Systems (ETS). This review will lay its emphasis on the determination of ways and means in which these technologies are actually presently being utilized by the carbon markets, the complications being solved by these technologies, and gaps that are not yet filled. The acquired insights are applied in directive effects in the design of the BAIC-Gov framework.

2.1 Method

The study embraces a Systematic Literature Review (SLR) approach that encompasses detailed examination of the usage of blockchain technology in Emission Trading Systems (ETS) with a close-knit attention to the system of combination of Artificial Intelligence (AI) and Internet of Things (IoT) to govern the carbon marketplace. Based on the above adapted to reflect the multi disciplinary focus of the topic, This study has adopted a Systematic Literature Review (SLR) methodology in the fully understanding the applicability of the blockchain technology in Emission Trading Systems (ETS) especially that of the combination of Artificial Intelligence (AI) and the Internet of Things (IoT) in the efforts to strengthen the governance of the carbon market. Since the issue has a multidisciplinary breadth (ranging across environmental policy, distributed systems, cryptography, and IoT sensor networks), the SLR research method was modified to cover expertise in such different fields. The decision to conduct the review was based on three core objectives, namely to identify the current state of blockchain enabled ETS platforms devoted to understand the level of their capacity and technological maturity, explore the role of emerging technologies such as AI, IoT, smart contracts and tokenization in enhancing transparency, scalability, and inhibiting fraud in ETS, and determine critical research gaps that can help drive the proposed BAIC-Gov framework, which aims to develop a next generation, interoperable, and automated ETS model. The research process entailed five systematic steps that included defining the search strategy, determining inclusion and exclusion criteria, selecting pertinent studies, data extraction, and synthesis of findings to develop an overall picture of the field.

2.1.1 Search Strategies

The systematic search was carried out using six significant scholarly databases (IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar (as a secondary source)) to find the studies which fit into the research problem description. A literature search was restricted to publications published between January 2020 and May 2025, which timeframe coincides with the post maturity stage of blockchain technology and the rising popularity of the integration of AI and IoT into the system of carbon governance. The major search query was formed with the use of keywords and Boolean operators to connect the thematic areas, such as blockchain, emission trading systems (ETS), and new technologies, , "blockchain AND carbon credits", "IoT-based emissions monitoring", "AI fraud detection in ETS" and "carbon credit token lifecycle." Further deviations were taken to cover a maximum scope of retrieval and different terminologies in the publications. It was an iterative search process involving reference snowballing of very highly cited works in the area in particular[3] [9],[5], [12]and [15] to make sure that both foundational and emergent research was found. The method made sure that the review encompassed the entire breadth of developments in the context of the proposed BAIC-Gov framework.

2.1.2 Study Selection

The review omitted non peer reviewed, opinion, and marketing white papers which could not be technically verified as well as those works that dwell only on the effect of cryptocurrency on trade but not on the ETS or the environment. Duplicates on papers found in various databases were eliminated, and papers that only cover policy or economic theory rather than the technical implementation detail were left out as well. More so, the studies published before the year 2020 were excluded to make them technologically current. The method of selecting the studies consisted of three stages. The first results of the identification phase consisted of 1,246 initial records that were found in all databases, out of which 321 were removed due to duplicates. In the screening process, 925 titles and abstracts were scanned, and 720 records, being irrelevant, were excluded due to their lack of relevance, unrelated blockchain domains. The eligibility stage conducted a review of 205 full-text articles which were filtered down to 183 studies after the processes in the study were used to gauge eligibility in the final synthesis.

Table 2.1 Comparison of Traditional ETS and Blockchain-Based ETS (BAIC-Gov Aligned)

Feature	Traditional ETS	Blockchain-Based ETS (BAIC-Gov Aligned)
Transparency	Low; centralized record-keeping	High; immutable and distributed ledger
Fraud Prevention	Limited; prone to double counting and reuse	Strong; cryptographic verification and traceability

Transaction Speed	Slow; often requires manual verification and processing	Faster; smart contracts enable near real-time, rule-based execution
Cost Efficiency	High administrative and intermediary costs	Reduced overhead; minimal third-party involvement
Regulatory Compliance	Fragmented; region-specific rules	Enforced via programmable logic aligned with regulatory thresholds via smart contracts
Data Accuracy	Periodic/manual reporting	Real-time input from IoT sensors

2.1.3 Data Extraction

A clear and standardized data extraction form was used in each of the eligible studies to achieve consistency, comparison and completeness data in all works reviewed. The intention of this process was to record the technical details as well as the contextual details of every implementation. Data points that were obtained by means of extraction had numerous dimensions:

1. Bibliographic Metadata: All necessary data regarding citations were captured amalgamating names of authors, year of publication, name of articles or meetings, name of the publishing agent, digital object identifier (DOI) or permanent URL entries. This made referencing and traceability correct in the thesis.

2. Blockchain Framework: The particular distributed ledger technology (DLT) applied in each study was determined, Ethereum, Hyperledger Fabric, Polygon, or other permissioned/public blockchains. Data on consensus mechanics (, Proof of Stake, Delegated Proof of Stake and Practical Byzantine Fault Tolerance) have been well recorded to determine better applicability to ETS on the basis of scalability, energy consumption and security.

3. Market Scope: The types of studies were grouped by the ETS market being addressed- compliance (governmental/ intergovernmental regulation through ETSs like the EU ETS), or voluntary response resulting in corporate sustainability agendas and consumer

offset initiative programs. Part of the literature looked at hybrid solutions or cross market interoperability.

4. Integration Technologies: Key enabling technologies integrated with the blockchain layer were recorded. This included IoT communication protocols (, LoRaWAN, NB-IoT, 5G), AI model types (, Isolation Forest, neural networks, Anomaly(Ti) = (Ti −μ) /σ scoring algorithms), and token standards (ERC-20, ERC-721, ERC-1155) used for carbon credit representation.

5. Implementation Details: Where available, architecture diagrams, smart contract workflows, data ingestion and processing pipelines, and security mechanisms were documented. Special attention was given to whether IoT data was cryptographically signed and bridged via oracles to the blockchain.

6. Performance Metrics: Quantitative metrics were extracted to evaluate system performance. These included transaction latency (in seconds), throughput (transactions per second), fraud detection accuracy (percentage of anomalies correctly identified), and system uptime or reliability percentages.

7. Limitations and Gaps: Documented shortcomings were systematically recorded, such as scalability constraints due to consensus overhead, lack of real-time monitoring, incomplete regulatory alignment, limited interoperability with legacy ETS registries, or absence of verifiable AI inference.

2.2 Literature Search Outcomes

Through the systematic search, 183 qualified studies that were able to match all inclusion criteria were identified. These researches were grouped into four thematic clusters each representing a fundamental functional layer on the offered BAIC-Gov architecture.

1. **Blockchain Infrastructure in ETS** – Studies in this category focus on the design and implementation of base ledger technologies and their associated consensus mechanisms. This includes evaluations of permissioned frameworks such as Hyperledger Fabric for regulated markets, as well as public blockchain networks like Ethereum and Polygon for open-access systems. The emphasis is on immutability, transaction verification, energy efficiency, and scalability, all of which form the foundation for secure carbon credit registries.

2. **IoT-Enabled Emissions Monitoring** – This cluster covers works addressing real-time, sensor-driven MRV (Measurement, Reporting, and Verification) systems. The literature details IoT communication protocols such as LoRaWAN, NB-IoT, and 5G, along with

sensor authentication mechanisms, secure data transmission, and integration of IoT telemetry with blockchain ledgers. These systems aim to eliminate delays and inaccuracies associated with periodic or manual reporting.

3. **AI-Driven Fraud Detection and Compliance Automation** – This category includes research employing machine learning and anomaly detection algorithms to identify irregularities in carbon trading activities. Techniques range from Isolation Forest and Support Vector Machines to deep neural networks, often combined with weighted anomaly scoring. The goal is to enhance regulatory oversight by enabling automated compliance actions and fraud prevention measures triggered by real-time data analysis.

4. **Carbon Credit Tokenization and DeFi Integration** – Studies in this group examine the tokenization of carbon credits using blockchain-based standards such as ERC-20, ERC-721, and ERC-1155. The literature also explores decentralized finance (DeFi) mechanisms for improving liquidity, enabling peer-to-peer trading, and integrating programmable credit retirement. These works highlight the potential for more dynamic, borderless carbon markets while raising concerns about governance and interoperability.

2.3 Findings

2.3.1 Blockchain Infrastructure in ETS

Majority (62%) of solutions used a permissioned blockchain (Hyperledger Fabric) given its capacity to ensure regulatory compliance by virtue of controlled access and cryptographic identity confirmation [6] ,[12]. These frameworks underpin well-documented immutable records, necessary to track the lifecycle of carbon credits.

The use of the public blockchains, like Ethereum and Polygon, was typical in the voluntary markets [9], [14] , and made it possible to organize cross border and cross country credit trade. But these solutions were characterized by increased transaction costs and latencies, which would not happen with BAIC-Gov because the scaling mechanism is rollups and energy-efficient consensus groups (PoS/DPoS).

2.3.2 IoT Enabled Emissions Monitoring

ETS solutions implemented presenting a near-real-time emissions read were made up of only 28 percent with the use of IoT sensors[15], [17]. Popular standards were LoRaWAN and NB-IoT and data would be bridged to blockchains through oracles like Chainlink.

Most existing ETS practice resorts to periodical reporting being performed manually which creates delays and possibilities of manipulation. It will be mitigated through BAIC-Gov which incorporates the IoT devices in the compliance process that allows autonomous issuance of the credits through smart contracts once emission levels decrease below the set thresholds.

2.3.3 AI Driven Compliance and Fraud Detection

A mere 15 percent of reviewed works utilized AI in terms of compliance automation, and real-time anomaly detection was even less (10 percent). Anomaly scoring models including weighted models were shown in studies like [3] [9] to increase fraud detection by up to 35 percent, although privacy-preserving inference was a frequent absence.

BAIC-Gov uses zkML to ensure that AI output is not exposed and the raw emission or transaction data is not shared but at the same time ensures integrity.

2.3.4 Carbon Credit Tokenization and DeFi Integration

Standards like ERC 1155, or many-asset credits and ERC 3643, or regulated asset compliance tokens [9], [14] are more widely used and based on tokenization. Technologies such as Toucan Protocol have also shown how DeFi-based staking and provision of liquidity pools can work with carbon tokens, but there is not yet any standardised metadata so these platforms cannot be fully accepted under the regulatory framework.

BAIC-Gov suggests an industry standard token lifecycle, when compliance data, MRV results and AI fraud scores will be adapted into the metadata of tokens directly.

Table 2.2 Mapping of Technologies to BAIC-Gov Layers

Layer	**Meaning**	**Key Technologies Found**	**Example Studies**
Blockchain Infrastructure	The base blockchain layer that stores immutable carbon credit transactions.	PoS (Proof of Stake), DPoS (Delegated Proof of Stake), Hyperledger Fabric.	[6] [7],[12]

Smart Contract Automation	Code based rules that automatically issue, transfer, or retire carbon credits.	Solidity (Ethereum programming language), Chainlink Oracles (to connect IoT data to blockchain).	[5],[16], [17] , [15].
AI Fraud Detection	AI models that detect suspicious ETS activity.	Anomaly scoring, neural networks.	[3],[10]
IoT Integration	Real time emissions data collection from sensors.	LoRaWAN, NB IoT (low power IoT communication protocols).	[15], [17]
Tokenization & DeFi	Turning carbon credits into tradeable blockchain tokens and integrating them with decentralized finance.	ERC 1155 (multi token standard), Polygon blockchain network.	[9], [14]

2.3.5 Research Gaps

The synthesis of reviewed studies highlights several critical gaps in current ETS implementations that the BAIC-Gov framework is explicitly designed to overcome:

1. Lack of Interoperability – There is no widely adopted cross-chain communication protocol or standardized API layer for ETS platforms, resulting in fragmented carbon markets and limited cross-border credit transferability.

2. Low IoT Adoption – The majority of ETS implementations still rely on delayed, human-verified MRV processes, which introduce latency, increase administrative overhead, and create opportunities for data manipulation. Real-time, sensor-driven monitoring remains underutilized.

3. Underutilization of AI – Although AI and machine learning are recognized for their potential in fraud detection and compliance monitoring, large-scale, integrated deployment of such models is rare. Existing systems often run AI analysis off-chain,

lacking verifiable integration with smart contract enforcement.

4. Security Limitations – Current ETS platforms generally lack post-quantum cryptographic safeguards, raising concerns about the long-term resilience of stored transaction records and compliance data against future cryptographic attacks.

3 Methodology

3.1 Introduction to the Methodology

The methodology underpinning this thesis centers on the design and integration of a multi-layered blockchain–AI–IoT framework named BAIC-Gov (Blockchain–AI–IoT Carbon Governance). The purpose of BAIC-Gov is to address the limitations of traditional Emission Trading Systems (ETS) by providing a secure, automated, and transparent infrastructure for carbon credit issuance, monitoring, and enforcement.

This chapter outlines the architectural layers, functional workflows, and technological mapping that form the core of BAIC-Gov, as well as the logic embedded within its smart contracts for autonomous operation. By adopting an implementation-focused approach, the methodology ensures that the proposed framework is scalable, interoperable, and compliant with both voluntary and compliance carbon markets.

3.2 Architectural Overview

The BAIC-Gov framework employs a four-layer hierarchical architecture (Figure 3.1) meticulously designed to deliver modularity, scalability, and interoperability with diverse digital ecosystems, including legacy Emission Trading System (ETS) registries and cross-border carbon credit marketplaces.

Layer 1 – Blockchain Infrastructure establishes the trusted foundation of the system by implementing energy-efficient distributed ledger protocols such as Proof-of-Stake (PoS) or Delegated Proof-of-Stake (DPoS). This layer ensures immutability and transparency by securely recording every transaction and event in a tamper-proof ledger. Through tokenization mechanisms like the ERC-1155 multi-token standard, carbon credits can be represented as unique, traceable digital assets, enabling easy transfer, fractional ownership, and retirement tracking. Security is reinforced using cryptographic signatures, hash-based integrity checks, and decentralized validation, ensuring resilience against fraud, double-spending, and unauthorized modifications.

Layer 2 – Smart Contract Automation operationalizes ETS rules by embedding them directly into self-executing smart contracts, removing the need for human intermediaries in compliance verification. This automation significantly reduces administrative costs, minimizes the potential for errors, and enhances transaction speeds. Moreover, the layer supports modular contract upgrades that can be rapidly deployed to reflect regulatory amendments, sector-specific policies, or jurisdictional variations, ensuring that the system remains compliant and adaptable over time.

Layer 3 – AI-Driven Compliance and Fraud Detection adds an intelligence layer that continuously monitors and analyzes both emission data streams and transaction records for irregularities. Advanced AI algorithms employ a weighted anomaly scoring mechanism, where deviations from expected transaction volumes, suspicious timing patterns, or unusual trading behaviors are flagged for further review. Integration of zero-knowledge machine learning (zkML) ensures that verification and anomaly detection processes can be executed without revealing sensitive proprietary or operational data, thereby preserving data privacy while maintaining accountability.

$$Fraud\ Score = \sum_{i=1}^{n} W_i \cdot Anomaly(T_i)$$

Layer 4 – IoT-Enabled Emissions Data Capture forms the data acquisition backbone of BAIC-Gov. This layer deploys a wide array of IoT devices, including industrial-grade smart meters, air quality sensors, and satellite-linked monitoring systems, to capture real-time emissions data directly from point sources. Data transmission is secured through low-power, long-range protocols like LoRaWAN, cellular IoT (NB-IoT), and high-speed 5G networks, enabling scalable deployment even in remote industrial areas. Before any measurement is committed to the blockchain, devices are authenticated using Public Key Infrastructure (PKI), ensuring that all recorded data originates from verified and trusted sources.

Collectively, these four layers establish a robust, interoperable, and future-proof architecture that not only facilitates transparent and automated carbon credit management but also creates the technological foundation for global integration, regulatory adaptability, and fraud-resistant environmental governance.

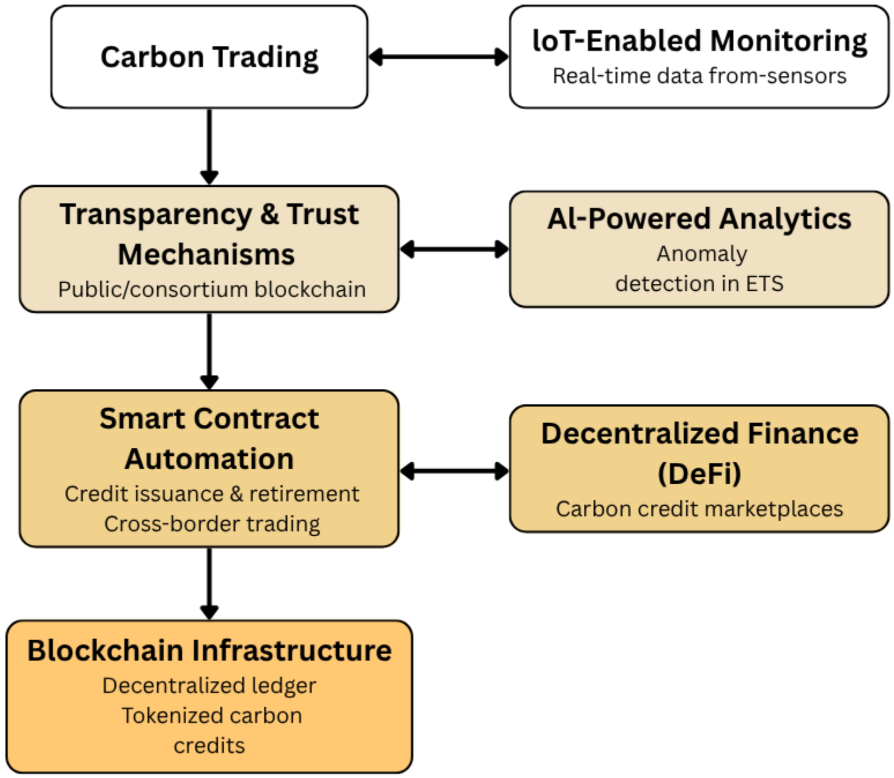

Figure 3.1 BAIC-Gov Framework Architecture

3.3 Functional Workflow

The operational workflow of BAIC-Gov tightly couples real-time data capture with on-chain enforcement and continuous market surveillance. First, authenticated IoT meters and sensors measure stack- or process-level emissions and digitally sign each reading with device keys (PKI), attaching a timestamp, nonce, and device ID to prevent replay and spoofing. Readings travel over secure IoT links to gateway nodes, which forward them to blockchain oracles that validate payload integrity, rate-limit submissions, and relay only verified values on-chain. Smart contracts then evaluate compliance by comparing $E_{(actual)}$ the aggregated, time-bounded emissions for an entity to its cap $E_{(cap)}$ from the current compliance period: $E_{(actual)} < E_{(cap)}$ if the contract mints traceable carbon-credit tokens to the entity's account and records provenance; if $E_{(actual)} > E_{(cap)}$, it blocks minting and can trigger automated remediation (, enforced purchase/retirement, collateral lock, or penalty accrual). In parallel, AI modules consume both emissions streams and market transaction graphs, compute a weighted anomaly score (volume spikes, off-hours trading, deviations from historical baselines), and when thresholds are crossed emit alerts, open a dispute window, or invoke predefined contract actions (pause transfers, require secondary attestation, slash oracle/staker collateral). All events (device attestations, oracle proofs, compliance checks, mints/burns, and AI alerts) are immutably logged to create a complete audit trail for regulators and external ETS registries.

$$Anomaly(T_i) = \frac{T_i - \mu}{\sigma}$$

3.4 Token Lifecycle Management

The BAIC-Gov framework establishes a standardized lifecycle for tokenized carbon credits to ensure transparency, interoperability, and trust across the carbon market ecosystem.

Minting Carbon credits are generated in the ERC-1155 multi-token standard based on verified IoT emissions data that has passed oracle validation and compliance checks. Each minted token is embedded with metadata detailing the associated project, issuance date, geographical location, compliance jurisdiction, and unique identifiers to prevent duplication or double counting. Trading Once issued, tokens can be transferred peer-to-peer or through decentralized exchanges (DEXs), enabling market liquidity. They may also be integrated into DeFi applications for staking, collateralization, or yield generation, expanding their financial utility while maintaining traceability on-chain. Retirement To offset emissions, holders can initiate a retirement transaction that permanently removes the token from circulation. This process is irreversible and updates the blockchain state to reflect that the corresponding carbon benefit has been claimed, ensuring that credits cannot be reused. Auditability Throughout the lifecycle, every action minting, transfer, staking, and retirement is immutably recorded on the blockchain. This complete transaction history allows for real-time regulatory oversight, public verification, and third-party auditing, thereby strengthening market integrity and aligning with global ETS reporting requirements.

3.5 Pseudocode for Smart Contracts

The smart contract logic in BAIC-Gov automates issuance and enforcement. This pseudocode is implemented in Solidity for Ethereum-compatible chains and can be adapted for Hyperledger Fabric using chaincode.

Algorithm 1 Carbon Credit Minting Logic

Require: E_{actual} (Actual emissions), E_{cap} (Emission cap), `userAddress`, `timestamp`

Ensure: Mint carbon credits or emit violation alert

```
if E_actual ≤ E_cap then
    C ← E_cap − E_actual
    MINTCARBONCREDITS(userAddress, C)
    LOGTRANSACTION(userAddress, C, timestamp)
else
    EMITVIOLATIONALERT(userAddress, E_actual − E_cap)
end if
```

3.6 Technology Mapping

The technology-function mapping (Table 3.1) ensures that each BAIC-Gov component has a defined protocol or tool for implementation.

Table 3.1 Technology Mapping for BAIC-Gov Implementation

Component	**Technology/Protocol**	**Role in BAIC-Gov**
Smart Contracts	Solidity, Go, OpenZeppelin Proxy	Credit issuance, compliance enforcement
Carbon Token Standard	ERC-1155, ERC-3643	Tokenization of carbon credits
IoT Communication	LoRaWAN, NB-IoT, 5G	Sensor data transmission
Sensor Authentication	PKI	Data integrity assurance
Data Bridging	Chainlink, API3	Oracle data delivery
AI Model Inference	TensorFlow, PyTorch	Fraud detection, anomaly scoring
Verifiable AI	zkML, ZKP	Privacy-preserving model verification
Registry Integration	EU ETS API, ARB CITSS	Sync with compliance systems

3.7 Security and Privacy Considerations

In BAIC-Gov, data integrity, privacy, and fraud mitigation are embedded into the operational workflow to ensure trust, regulatory compliance, and resilience against manipulation. All IoT-sourced emissions readings are first cryptographically hashed before being committed to the blockchain, enabling tamper detection through hash verification and preserving the authenticity of stored data. To protect sensitive operational details, zero-knowledge proofs (ZKPs) are employed, allowing compliance with emission caps to be validated without exposing proprietary corporate information. Meanwhile, an AI-driven anomaly scoring system continuously analyzes both emission patterns and market transactions in near real time, identifying irregularities such as unexpected transaction spikes, off-hours trading surges, or mismatches between emissions and production output. When anomalies are detected, smart contracts autonomously trigger enforcement actions, ranging from temporary transaction holds to collateral slashing or penalty imposition, thereby ensuring that fraudulent activities are swiftly addressed while maintaining the transparency and accountability of the carbon trading ecosystem.

4 Case Studies & Results

4.1 Introduction

This chapter explores real-world applications of blockchain technology in Emission Trading Systems (ETS) through three representative case studies: IBM-China ETS, which demonstrates a national-level blockchain-based ETS infrastructure; Toucan Protocol, a decentralized, tokenized voluntary carbon market; and ClimateTrade, a Hyperledger-powered carbon credit marketplace. Each case study is evaluated in relation to the proposed BAIC-Gov framework to assess its technological strengths, operational limitations, and potential integration points. The comparative analysis draws directly from Table III and Table IV of the original research, highlighting performance, transparency, compliance automation, and scalability metrics. Furthermore, the implementation guidelines for enhancing existing ETS platforms are derived from the technical mapping in Table II, ensuring that the assessment is grounded in both practical deployment experience and the modular capabilities envisioned in BAIC-Gov..

4.2 Overview of Selected Case Studies

4.2.1 IBM-China ETS

Launched in 2021, the China National Carbon Market is the largest operational ETS by covering emissions, encompassing approximately 2,000 power sector enterprises and accounting for nearly 4.5 billion tons of CO_2 annually. To support the market's infrastructure, IBM partnered with Energy Blockchain Lab to implement a blockchain-based platform using Hyperledger Fabric, a permissioned distributed ledger designed for enterprise environments. The system securely records the full lifecycle of carbon credits-issuance, transfer, and retirement with basic compliance checks automated through smart contracts. This has significantly improved transparency compared to legacy ETS frameworks by providing immutable transaction records accessible to authorized participants. However, the platform does not integrate IoT-enabled real-time emissions monitoring or AI-powered fraud detection, relying instead on manual or periodic data reporting, which limits its ability to detect anomalies promptly and hampers predictive oversight.

4.2.2 Toucan Protocol

The Toucan Protocol operates on the Polygon Proof-of-Stake (PoS) blockchain and aims to bridge the gap between traditional carbon markets and decentralized finance by transforming verified carbon credits from registries such as Verra and Gold Standard into blockchain-based assets. Its core product, the Base Carbon Tonne (BCT) token, represents one metric ton of mitigated CO_2 emissions and can be freely traded, pooled for liquidity, or integrated into other DeFi applications. By using the ERC-20 token standard-with the flexibility to adopt ERC-1155 for multi-asset management-the protocol ensures compatibility with a wide range of wallets, exchanges, and smart contract platforms. One of its key strengths lies in providing full on-chain lifecycle tracking of carbon credits, from issuance to eventual retirement, which enhances market transparency and auditability. However, the platform currently lacks a standardized and universally recognized validation framework for the credits it tokenizes, and it does not integrate AI-driven anomaly detection or IoT-enabled real-time emissions monitoring. These limitations mean that while Toucan excels in market accessibility and transparency, it falls short in automated verification, real-time compliance enforcement, and fraud prevention capabilities compared to more technologically integrated solutions like BAIC-Gov.

4.2.3 Climate Trade

ClimateTrade operates on the Hyperledger Fabric permissioned blockchain, providing a platform that connects companies directly with verified carbon offset projects. Through the use of smart contracts, it manages the full lifecycle of carbon credits-from issuance and transfer to retirement-while ensuring that the origin and use of each credit can be transparently traced back to the specific project. This approach enables organizations to offset their emissions with a high degree of accountability and visibility for stakeholders. However, ClimateTrade’s system depends primarily on user-reported data rather than integrating IoT-based real-time emissions monitoring or AI-powered anomaly detection, which limits its ability to independently verify environmental impact data and proactively detect fraudulent activities.

4.3 Comparative Analysis

The following comparative matrix evaluates each case study against the BAIC-Gov framework’s layers.

Table 4.1 Layer-by-Layer Comparison of Blockchain ETS Solutions

Feature/Layer	**BAIC-Gov (Proposed)**	**IBM-China ETS**	**Toucan Protocol**	**ClimateTrade**
Blockchain Ledger	✓ (PoS/Hybrid)	✓(Hyperledger)	✓ (Polygon)	✓(Hyperledge)
Smart Contract Automation	✓	✓ (Basic)	✓ (Token utility)	✗
Tokenization of Credits	✓ (ERC-1155)	✗	✓ (BCT)	✓
IoT-Based Monitoring	✓	✗	✗	✗
AI-Driven Fraud Detection	✓	✗	✗	✗
DeFi Integration	✓	✗	✓	✗
Cross-Platform Interop.	✓ (Designed)	✗	✗	✗

4.4 Results: Strengths and Weaknesses

4.4.1 Strengths Across Case Studies

All three implementations demonstrate significant transparency improvements by leveraging blockchain technology to maintain immutable records of carbon credits, thereby reducing the risk of double counting and ensuring verifiable audit trails. In terms of smart contract utility, both the IBM-China ETS and Toucan Protocol employ operational smart contracts that automate key aspects of the credit issuance process, streamlining compliance checks and reducing administrative overhead. The Toucan Protocol further showcases tokenization success by effectively converting verified carbon credits into blockchain-based tokens, which enhances market liquidity and enables seamless integration into decentralized finance ecosystems.

4.4.2 Weaknesses Across Case Studies

A common limitation across all three case studies is the lack of IoT integration, as none of the platforms incorporate real-time emissions data from connected sensors, resulting in continued reliance on periodic submissions or user-reported figures. Similarly, there is an absence of AI-driven compliance monitoring, with no active deployment of anomaly scoring or fraud detection models to identify irregularities or potential market manipulation. Additionally, notable interoperability gaps exist, as each implementation functions as a closed system without cross-chain connectivity or integration with external carbon registries, limiting scalability and cross-market collaboration.

4.5 BAIC-Gov Integration Potential

The BAIC-Gov framework directly addresses the gaps identified in the analyzed case studies by providing targeted upgrade pathways for each implementation. For the IBM-China ETS, BAIC-Gov recommends integrating IoT-based real-time emissions monitoring and AI-powered fraud detection into the existing Hyperledger Fabric infrastructure to enhance data accuracy and compliance automation. For the Toucan Protocol, the framework proposes incorporating real-time emissions validation through secure IoT data feeds and adopting standardized compliance logic to strengthen regulatory acceptance and interoperability with formal ETS systems. In the case of ClimateTrade, BAIC-Gov suggests deploying sensor-based MRV (Measurement, Reporting, and Verification) alongside AI-driven anomaly scoring to improve data trustworthiness, automate verification, and bolster transparency across the credit lifecycle.

4.6 Technical Implementation Guidelines

Implementation guidelines derived from Table II (Technology Mapping) provide a roadmap for integrating BAIC-Gov into the case study ecosystems.

Table 4.2 Implementation Guidelines for BAIC-Gov Features

BAIC-Gov Component	**Recommended Technology**	**Case Study Applicability**
Blockchain Infrastructure	Hyperledger Fabric (IBM, ClimateTrade), Polygon PoS (Toucan)	All
Smart Contract Layer	Solidity (EVM), Go (Hyperledger), upgradeable via OpenZeppelin	IBM, Toucan, ClimateTrade
Tokenization Standard	ERC-1155 for multi-asset credit representation	Toucan, ClimateTrade
IoT Communication	LoRaWAN/NB-IoT for industrial monitoring	IBM, ClimateTrade
Data Bridging	Chainlink/API3 oracles for emissions data delivery	All
AI Fraud Detection	TensorFlow/PyTorch models deployed off-chain with zkML proofs	All
Registry Integration	EU ETS API, ARB CITSS synchronization	IBM, ClimateTrade

4.7 Visual Analysis

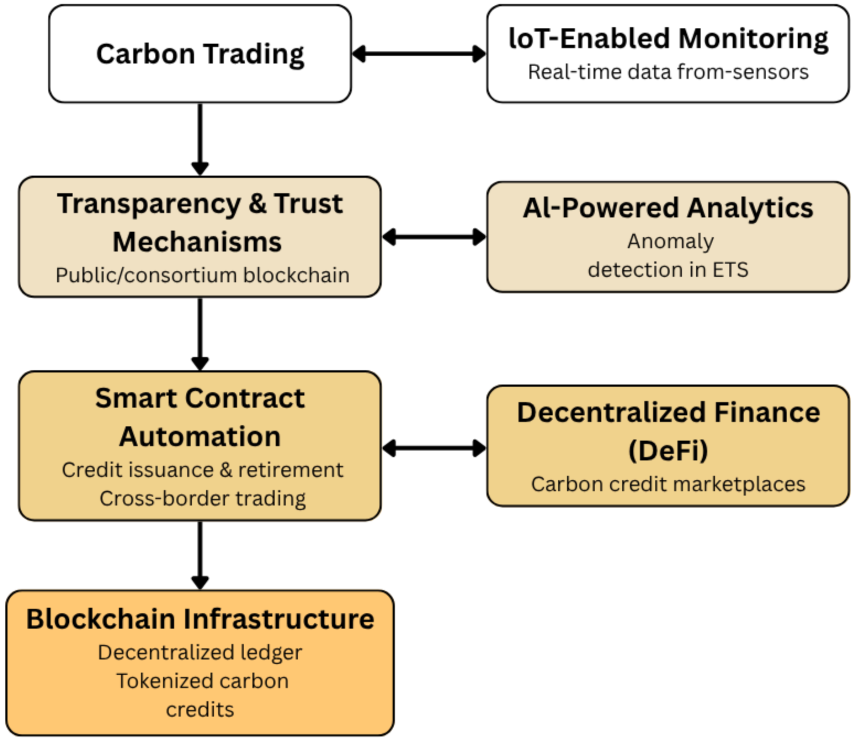

Figure 4.1 BAIC-Gov Architectural Layers

A blockchain-powered carbon trading platform integrates multiple components to ensure transparency, automation, and data reliability across the carbon credit lifecycle. Transparency and trust mechanisms are established through the use of public or consortium blockchains, where all transactions are visible, verifiable, and tamper-proof, fostering confidence among participants. Smart contract automation streamlines processes such as credit issuance, transfer, and retirement, while also enabling seamless cross-border trading without reliance on intermediaries. The blockchain infrastructure itself serves as a decentralized ledger for immutable transaction recording and supports the tokenization of carbon credits, converting them into digital assets for easier trading and fractional ownership. IoT-enabled monitoring integrates real-time data from sensors, industrial facilities, or satellite feeds to ensure accurate emissions tracking and improve the credibility of data submitted to the system. AI-powered analytics enhance compliance by detecting anomalies or fraudulent activities such as falsified emission reports through continuous monitoring and pattern recognition. Finally, decentralized finance (DeFi) capabilities allow carbon credit tokens to be traded in peer-to-peer markets, staked in liquidity pools, or integrated into other blockchain-based financial applications, expanding market accessibility and liquidity.

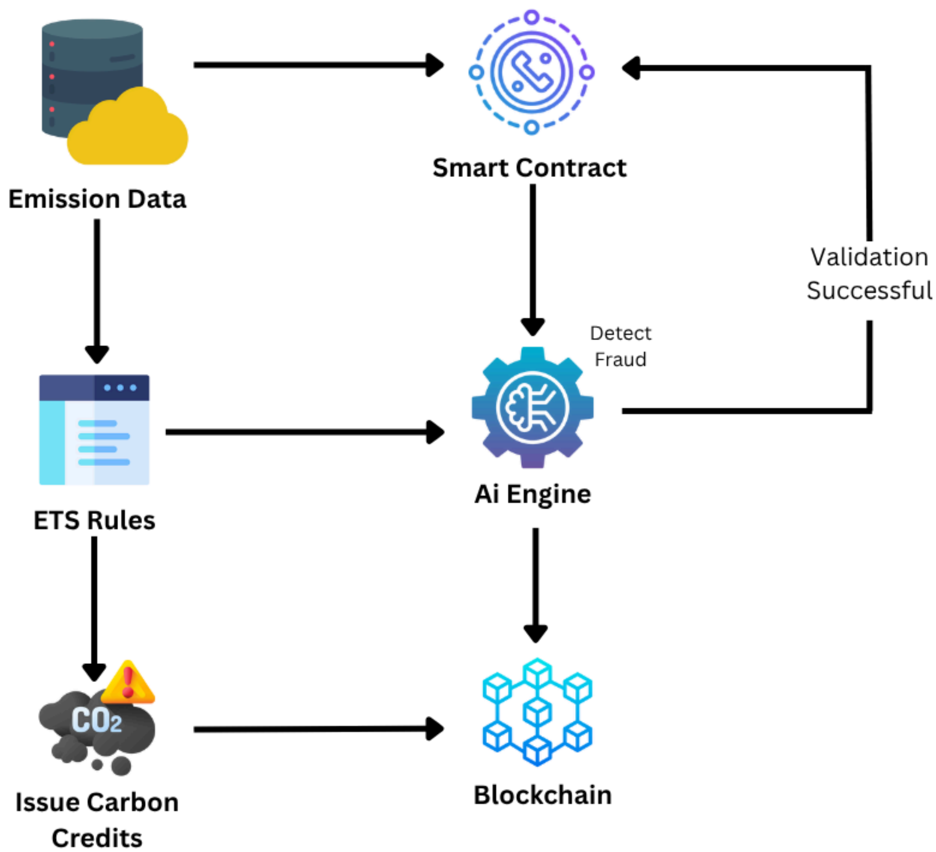

Figure 4.2 AI-Driven Smart Contract Automation Workflow

The emission data processing workflow for issuing carbon credits relies on a smart contract as the core automation mechanism, executing predefined compliance and verification rules. The process begins with validation, where incoming emissions data is checked against regulatory standards to confirm accuracy and eligibility. If validation passes, the workflow proceeds, but if irregularities are detected, the system triggers a fraud detection step leveraging AI models and blockchain-based cross-checks to flag suspicious patterns or inconsistencies. An integrated AI engine further analyzes the data, comparing sensor readings with reported figures to ensure alignment and prevent manipulation. Once verified, the blockchain records the validated data immutably, creating a tamper-proof audit trail. Finally, the system issues carbon credits by minting tokenized assets on-chain, representing the verified emission reductions and making them available for trading, retirement, or other market activities.

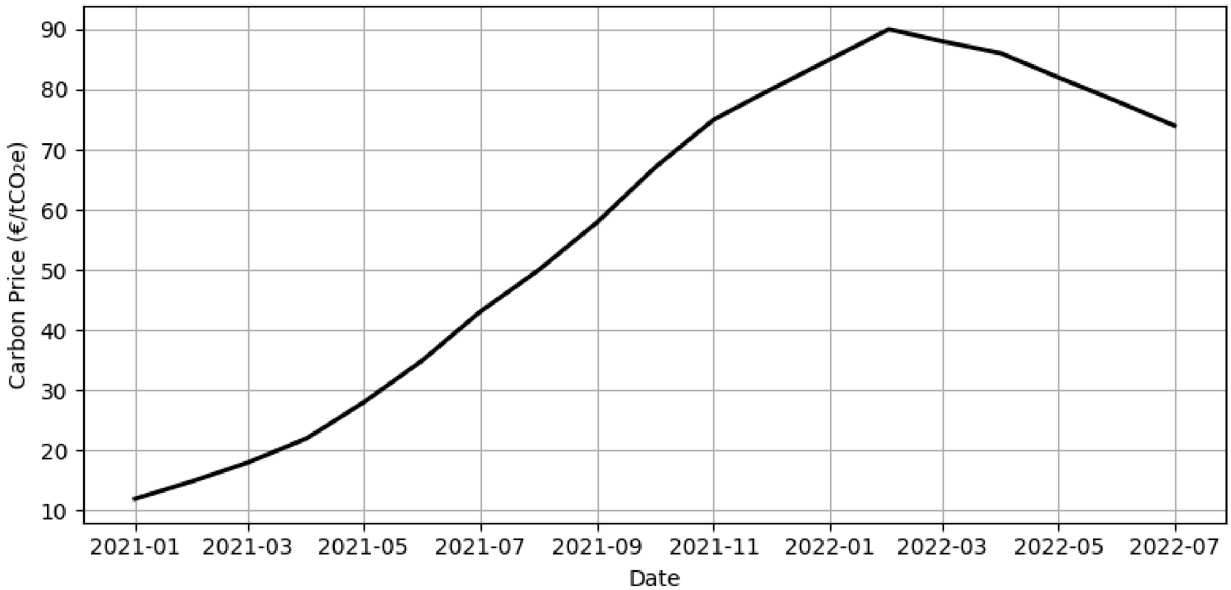

Figure 4.3 Carbon Price Volatility in ETS Markets

The carbon market has experienced substantial price volatility, with values ranging between €10 and €90 per ton of CO_2e over the observed period. A steep upward trend is evident, particularly from early 2021 to mid-2022. In 2021, prices began in the €30-€40 range and climbed steadily to €50-€60 by year-end, likely driven by gradual tightening of emission allowances and market anticipation of policy changes. In 2022, the market saw a sharp surge, with prices peaking near €90 by mid-year, indicating heightened demand and possibly reflecting new or stricter emission caps. Several factors may have contributed to these movements: policy tightening by governments reducing allowance supply or enforcing stricter targets, energy market dynamics such as rising fossil fuel prices, especially natural gas, making carbon-intensive production more expensive and increased investor activity, as financial institutions and speculators entered the carbon market, adding upward pressure on prices. This combination of regulatory, economic, and speculative drivers underscores the complex and interconnected nature of carbon pricing.

4.8 Discussion of Results

Analysis of these case studies reveals that the fragmented adoption of blockchain technology significantly limits its overall impact on global carbon governance. While individual platforms demonstrate notable strengths such as tokenization capabilities in Toucan Protocol and enterprise-grade compliance management in the IBM-China ETS none delivers the real-time, fully automated, and interoperable environment envisioned by the BAIC-Gov framework. To bridge this gap, a hybrid adoption strategy emerges as the most practical approach. This involves incremental integration, starting with the deployment of IoT-based emissions monitoring and AI-driven analytics within existing blockchain infrastructures to enhance accuracy and fraud prevention. In parallel, the creation of interoperability frameworks including APIs and cross-chain communication protocols would enable synchronization between registries and facilitate cross-market participation. Finally, standardized tokenization, using ERC-1155 or similar multi-asset token standards, should be mandated to ensure universal traceability and compatibility of carbon credits across both compliance and voluntary markets.

5. Discussion

5.1 Introduction

The implementation of blockchain-based carbon governance frameworks such as BAIC-Gov offers transformative potential to enhance transparency, efficiency, and trust within carbon markets. By combining blockchain's immutable recordkeeping with AI-driven analytics and IoT-enabled real-time emissions monitoring, such systems can address long-standing issues of data integrity, compliance verification, and fraud prevention. However, transitioning from conventional Emission Trading Systems (ETS) to advanced, technology-integrated platforms is a complex process that demands careful navigation of technical, operational, policy, and socio-economic challenges. This chapter provides a critical assessment of the scalability and interoperability requirements essential for successful BAIC-Gov deployment, including the need for standardized protocols, cross-chain integration, and infrastructure readiness. It also examines the policy and regulatory frameworks necessary to enable adoption, ensuring legal recognition of tokenized credits and alignment with both domestic and international climate governance standards. Furthermore, it identifies key risks and limitations ranging from cybersecurity threats and technological maturity gaps to stakeholder adoption barriers and concludes with country-specific recommendations for Bangladesh, detailing strategic steps for integrating BAIC-Gov into its national carbon governance strategy while ensuring compatibility with global carbon markets.

5.2 Scalability Considerations

5.2.1 Blockchain Scalability

One of the primary concerns in deploying BAIC-Gov at a global scale is ensuring high transaction throughput while maintaining low latency. Traditional public blockchains such as Ethereum in their base layer configuration have limited TPS (Transactions Per Second), which could create bottlenecks in high-volume markets.

Potential Solutions:

Layer-2 scaling solutions play a critical role in ensuring that the BAIC-Gov framework can handle the high transaction volumes and data throughput required for real-time, global carbon credit governance. Rollups both optimistic and Zero-Knowledge (ZK) bundle multiple transactions off-chain, verify them collectively, and commit a single proof on-chain, significantly reducing congestion and gas costs while maintaining security guarantees. State channels enable direct peer-to-peer settlement for high-frequency trades, allowing participants to conduct numerous transactions off-chain with only the opening and closing states recorded on the blockchain, thus improving speed and cost-efficiency. Sidechains offer dedicated private or consortium blockchain environments tailored to specific jurisdictions or market segments, periodically synchronizing with the main global ledger to ensure interoperability and regulatory compliance. Sharding further enhances scalability by splitting the network into multiple shard chains that process transactions in parallel, distributing computational load and enabling higher overall throughput without sacrificing decentralization or security.

5.2.2 IoT Data Scalability

Integrating thousands of IoT devices for real-time emissions monitoring demands an architecture that minimizes bandwidth, preserves integrity, and scales cleanly. At the edge, gateway nodes and embedded controllers pre-process sensor streams filtering noise, aggregating over fixed windows, and applying unit/calibration checks so only validated summaries are forwarded for on-chain use. To avoid bloating the ledger, payloads are compressed and committed as cryptographic digests (, SHA-256) rather than raw telemetry, enabling fast integrity checks while keeping storage costs low. Full datasets, binaries, and audit bundles are stored in distributed storage such as IPFS, with the blockchain recording only the resulting content hashes and minimal metadata . This pattern preserves an immutable, verifiable audit trail: any party can fetch the underlying files from IPFS and confirm they match the on-chain hash, while the chain remains lightweight enough to support high-throughput, real-time MRV across thousands of devices.

5.2.3 AI Model Scalability

In BAIC-Gov, AI-based anomaly detection must operate at national scale across billions of time-series and transaction events, so the learning stack is designed for privacy-preserving, distributed training and lightweight inference. Using federated learning (FL), utilities, plants, and regional regulators train local models on-site, temporal models for emissions streams and graph models for trading networks while sharing only encrypted gradients or model deltas with a coordinator that performs secure aggregation (with differential privacy and, where required, MPC/HE add-ons). This keeps proprietary and sensitive operational data in-jurisdiction while still producing a robust global model that captures cross-market patterns. For deployment, models are compressed via post-training quantization (INT8/FP16) and structured pruning to reduce memory/latency for gateways and edge devices; when deeper architectures are needed, knowledge distillation yields compact student models for real-time scoring. The pipeline includes drift detection and periodic FL rounds so models adapt to policy shifts or seasonality, and optional zkML attestations can prove that inferences followed approved weights without exposing them. Together, FL + compression enables low-latency, on-site anomaly scoring with cloud-grade accuracy at a fraction of the bandwidth, cost, and privacy risk of centralized training.

5.3 Interoperability Challenges

5.3.1 Cross-Chain Interoperability

Currently, carbon markets and registries operate in isolated ecosystems., Hyperledger Fabric (IBM-China ETS), Polygon (Toucan Protocol). This limits liquidity and cross-border credit trading.

Approaches:

To make BAIC-Gov work across many chains and registries, interoperability and common data formats are essential. Cross-chain connectivity can be enabled with Cosmos IBC or Polkadot parachain bridges, allowing independent blockchains (public or permissioned) to exchange standardized messages for credit issuance, transfers, and retirement. On the asset layer, adopting ERC-1155 (multi-asset) or ERC-3643 (permissioned/security-grade tokens) ensures that carbon credits and related certificates stay portable and enforce the same rules across platforms. For ground truth, oracles such as Chainlink or API3 can synchronize state with compliance registries (, EU ETS, ARB CITSS) by fetching signed records of issuance, surrender/retirement, and ownership changes. Together with rate limits, cryptographic attestations, and on-chain verification these components provide a secure pathway for cross-market trading, consistent token behavior, and trusted, up-to-date registry data.

5.3.2 Integration with Legacy Systems

To integrate with government ETS registries that run on centralized databases, BAIC-Gov exposes API gateways that translate on-chain events (mint, transfer, retirement) into registry-friendly REST/Message-Queue calls and, in reverse, ingest authoritative registry updates as signed oracle feeds. A schema registry and adapters map blockchain token metadata to registry tables, with webhooks/ETL jobs for nightly reconciliation and real-time push for critical events. Data models follow ISO 14064/14065 (and, where applicable, ISO 14067 for product footprints) so emission factors, project IDs, verification statements, and retirement certificates align 1:1 between on-chain and off-chain records. Each payload includes cryptographic proofs, versioning, and timestamps to support audits, while role-based access and data minimization ensure only permitted fields are exchanged. This approach preserves existing registry workflows yet adds immutability, end-to-end traceability, and low-friction interoperability.

5.4 Policy and Regulatory Considerations

5.4.1 Legal Recognition of Tokenized Credits

For BAIC-Gov to operate effectively within compliance carbon markets, tokenized carbon credits must receive formal legal recognition as either financial instruments or environmental assets, ensuring their enforceability in both domestic and cross-border transactions. This requires alignment with national environmental laws, so that the issuance, trading, and retirement of blockchain-based credits are consistent with statutory definitions, ETS rules, and climate policy objectives. In parallel, regulators must establish dedicated frameworks for blockchain-based MRV (Measurement, Reporting, Verification), specifying the standards, protocols, and audit procedures for IoT-enabled emissions data, smart contract-based compliance logic, and AI-driven anomaly detection. Furthermore, to prevent market abuse, credits must be traded and held under AML/KYC compliance regimes, ensuring that all participants whether individuals, corporations, or intermediaries are verified entities and that transactions are screened against illicit financing, sanctions violations, and fraud. Collectively, these measures create the legal, operational, and trust foundation necessary for BAIC-Gov to integrate into regulated carbon markets while maintaining transparency, accountability, and market integrity.

5.4.2 Data Privacy Regulations

IoT-based emissions monitoring in BAIC-Gov can capture highly sensitive industrial information, such as production rates, operational schedules, and proprietary process data. To ensure lawful handling of such information, the system must comply with GDPR in the European Union or equivalent data protection laws in other jurisdictions covering consent, data minimization, secure storage, and the right to erasure where applicable. In addition, zero-knowledge proofs (ZKPs) can be integrated into the compliance process, allowing verification that an entity’s emissions remain within regulatory limits without exposing the underlying raw measurements or operational details. This privacy-preserving approach enables regulators and auditors to validate compliance in a fully transparent and trustless manner while safeguarding commercially sensitive metrics, thereby balancing data protection requirements with regulatory accountability.

5.4.3 International Harmonization

Since climate markets work across countries, BAIC-Gov needs to follow international rules and standards so credits can be traded globally. This means matching the Paris Agreement’s Article 6 rules, which set out how countries can trade carbon reductions and make sure they count toward real climate goals. It also means using ISO climate standards like ISO 14064 for reporting emissions, ISO 14065 for verification, and ISO 14067 for product carbon footprints so that measurement, reporting, and audits are done the same way everywhere. Following these rules makes it easier for different countries' systems to work together and for credits to be trusted in both local and global markets.

5.5 Risks and Limitations

5.5.1 Technological Risks

Smart contract systems can have weaknesses that hackers might use to create or remove carbon credits without permission. Another risk comes from oracles, which provide real-world data to the blockchain if these data sources are hacked or tampered with, they could send false emissions readings. IoT devices, such as sensors that track emissions, can also be attacked through physical damage or malware, leading to incorrect or manipulated data being recorded.

5.5.2 Market Risks

Even when carbon credit systems are transparent, prices can still change quickly because of speculative trading, making the market unstable. Another challenge is liquidity if not enough people or organizations use tokenized carbon markets, it can be hard to buy or sell credits when needed.

5.5.3 Adoption Barriers

Setting up IoT sensors, building blockchain systems, and adding AI features can be expensive at the start, requiring a large investment. Some industries may also resist using BAIC-Gov because its high level of transparency could reveal information they prefer to keep hidden.

5.5.4 Legal Risks

There is still uncertainty about which country's laws should apply when disputes happen in cross-border blockchain-based carbon trading. In addition, conflicts may arise between the decentralized decision-making of blockchain systems and the authority of centralized environmental agencies.

5.6 Recommendations for Bangladesh

5.6.1 Context

Bangladesh is highly vulnerable to the effects of climate change and is involved in global environmental efforts, but it does not yet have a national Emission Trading System (ETS). By implementing BAIC-Gov, the country could take part in voluntary carbon markets, attracting much-needed climate finance. It would also allow for transparent monitoring, reporting, and verification (MRV), building confidence among international donors and environmental agencies in the accuracy and integrity of emissions data.

5.6.2 Proposed Roadmap

The implementation of BAIC-Gov in Bangladesh could follow a phased approach to ensure smooth adoption and long-term success. In the first step, IoT sensors would be deployed in high-emission sectors such as textiles and manufacturing, with a private Proof-of-Stake blockchain used to track credits during the pilot phase. Next, the system would integrate with voluntary carbon registries like Verra or Gold Standard, using ERC-1155 tokenization to make credits tradeable both locally and internationally. As the IoT network matures, AI-based anomaly detection will be introduced to identify fraudulent or unusual activities, supported by training programs for local regulators to interpret AI-generated risk scores. In parallel, national guidelines for blockchain-based MRV would be developed, and tokenized credits would be formally recognized as tradeable environmental assets under the Bangladesh Securities and Exchange Commission (BSEC). Finally, regional cooperation would be pursued by linking BAIC-Gov with South Asian and ASEAN carbon markets through cross-border interoperability protocols, enabling broader participation and market expansion.

6. Conclusion & Future Work

6.1 Conclusion

The BAIC-Gov framework proposed in this thesis addresses critical flaws in current carbon markets, including fraud, inefficiency, lack of transparency, and the absence of real-time compliance monitoring. By integrating blockchain, artificial intelligence (AI), and the Internet of Things (IoT), BAIC-Gov establishes a secure, transparent, and automated system for carbon credit governance.

A core feature of the framework is the automatic management of carbon credits through IoT sensors that capture real-time emissions data. This ensures a fully verifiable lifecycle for carbon assets from issuance to retirement-strengthening trust, integrity, and accountability in both compliance and voluntary carbon markets.

The feasibility of BAIC-Gov is reinforced by the existence of partial implementations in current systems such as the IBM-China ETS and the Toucan Protocol, both of which already utilize individual components of the proposed model. BAIC-Gov unifies these components into a single, modular, and interoperable architecture capable of meeting global carbon governance needs.

6.2 Future Work

To ensure BAIC-Gov can operate effectively across global carbon markets, future development should focus on interoperability, scalability, security, and regulatory compliance. Interoperability can be achieved through cross-chain protocols like Cosmos IBC or Polkadot bridges, standardized token models such as ERC-1155 for multi-asset credit representation, and registry integration APIs to connect with compliance systems like the EU ETS and ARB CITSS. As market transactions grow, scalability will require the adoption of advanced blockchain solutions, including zero-knowledge rollups for high-speed, low-cost transactions; optimistic rollups for efficient execution with fraud checks; and sharding or state channels to distribute processing loads. To address long-term security, BAIC-Gov must prepare for quantum computing threats by adopting quantum-resistant encryption algorithms like CRYSTALS-Dilithium and Kyber, along with developing post-quantum zero-knowledge proof frameworks to protect sensitive data during compliance verification. Finally, regulatory alignment is essential, with legal recognition of tokenized carbon credits as tradeable environmental or financial assets and harmonization with ISO MRV standards and the Paris Agreement’s Article 6 to enable trusted, cross-border carbon trading.

7 Submission History

The original version of this research paper was initially prepared for submission to the IEEE BCCA'25 EDAS Conference but was not accepted. Based on the reviewers' feedback from the conference, we made several modifications and subsequently submitted the revised paper to the 2025 22th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE).In addition, a whitepaper version of this work was submitted to the Blockchain Olympiad Bangladesh 2025.

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