Intelligent Blockchain for Managing Carbon Credits

by Inam Alanazi

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of philosophy

under the supervision of Associate Professor Farookh Hussain and Dr Firas Al-Dogman

University of Technology Sydney
Faculty of Engineering and Information Technology

May 2024

CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Inam Alanazi, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Signature: Inam

Production Note:
Signature removed prior to publication.

Date: May 2024

Acknowledgements

In the name of Allah, the Most Gracious, the Most Merciful. I begin by expressing my deepest gratitude to Allah, the Lord of all worlds, whose boundless blessings and guidance have paved the path for my achievements. As I reflect on the culmination of my aspirations, I am humbled by the immense support and guidance bestowed upon me by those who have played significant roles in my journey.

First and foremost, I extend my sincerest thanks to Professor Farookh and Dr. Firas, my esteemed thesis supervisors, whose mentorship transcended the confines of academia. Professor Farookh and Dr. Firas' unwavering guidance, patience, and belief in my potential have been instrumental in shaping my academic and personal growth. Their roles as mentors, elder brothers, and esteemed academic figures have been invaluable. I am deeply grateful for their encouragement, wisdom, and unwavering support, without which this journey would have been insurmountable.

To my beloved family, I offer my heartfelt appreciation. To My Mum, whose love, sacrifices, and unwavering belief in my abilities have been the cornerstone of my journey, I owe an immeasurable debt of gratitude. To my devoted husband Meshari, whose unwavering support, encouragement, and sacrifices have been my source of strength, I am eternally grateful. Your presence in my life has been a constant source of inspiration and motivation. To my dear children, Qusay, Yaqut, Ruba and Yaqeen, whose innocent smiles and boundless love have been my guiding light, I am endlessly thankful. You have been my driving force and my greatest joy.

I also extend my gratitude to my friends, whose camaraderie, support, and encouragement have enriched my experience and made this journey all the more meaningful.

I am also indebted to the University of Technology Sydney (UTS) for providing me with the platform to pursue my academic aspirations. UTS has been more than an institution of learning; it has been a nurturing environment that has fostered my intellectual curiosity and growth.

once again, I acknowledge with humility and gratitude the profound impact of each individual mentioned above in shaping my academic and personal journey. Their unwavering support, guidance, and encouragement have been instrumental, and I am deeply thankful for their presence in my life.

Inam Alanazi

Sydney, Australia, 2024.

List of Publications

The following is a list of my research papers during my PhD study, including those accepted for publication, as well as those currently under review or submitted.

Journal Papers

J-1. **I**nam Alanazi, Firas Al-Dogman and Farookh Khadeer Hussain (Augest,2023). Intelligent blockchain for managing carbon credits: Systematic literature Review, *InderScience, International Journal of Web and Grid Services*, (under review).

J-2. **I**nam Alanazi, Firas Al-Dogman and Farookh Khadeer Hussain. (May,2024) The double counting sentry, *The Journal of Knowledge-based systems* (submitted)

J-3. **I**nam Alanazi, Firas Al-Dogman and Farookh Khadeer Hussain. (May,2024) The Green credit Hub, A Marketplace for carbon credits, *The Journal of Internet of Things* (submitted)

Conference Papers

C-1. **A**lanazi, I., AL-Doghman, F., Alsubhi, A., & Hussain, F. (2024, April). Carbon Credits Price Prediction Model (CCPPM). In International Conference on Advanced Information Networking and Applications (pp. 143-150). Cham: Springer Nature Switzerland.

C-2. **A**lsobhi, H., Mirdad, A., Alotaibi, S., Almadani, M., Alanazi, I., Alalyan, M., ...& Hussain, F. K. (2021, May). Innovative Blockchain-Based Applications-State of the Art and Future Directions. In International Conference on Advanced Information Networking and Applications (pp. 323-335). Cham: Springer International Publishing.

ABSTRACT

Intelligent Blockchain for Managing Carbon Credits

by

Inam Alanazi

In recent years, the urgency to combat climate change has intensified, prompting increased attention towards carbon markets as a means to incentivise emission reduction efforts. However, the efficacy of these markets has been hindered by various challenges, including the problem of double counting, uncertainty in future price predictions, and the lack of a trusted marketplace infrastructure. This research examines the role of a novel platform that integrates blockchain technology to effectively mitigate these challenges.

Firstly, the platform addresses the issue of double counting by implementing a transparent and immutable ledger system, ensuring that each carbon credit is uniquely identified and accounted for throughout its lifecycle. In experiments, the system accurately identified 500 unique carbon credits and flagged 50 duplicates, effectively preventing double counting within the single project as well as across multiple projects. Secondly, the platform's predictive pricing feature, utilizing machine learning models like Random Forests and Support Vector Regression (SVR), achieved high accuracy in forecasting carbon credit prices with mean absolute errors (MAE) as low as 0.0115 and R^2 scores close to 1. These results highlight the model's robustness in capturing market trends.

Lastly,the platform also provides a secure marketplace for carbon trading, enhancing transparency and trust through blockchain's decentralized infrastructure.

Through a comprehensive analysis of the platform's features and functionalities, this research demonstrates how blockchain, coupled with advanced algorithms, im-

proves the efficiency, transparency, and reliability of carbon credit management and trading, offering a scalable solution to existing challenges.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

Human activity is one of the main drivers of climate change which is a significant threat to human wellbeing. Scientific predictions paint a grim picture of the future, warning of severe con- sequences if immediate action is not taken to address this (Mohanty, 2021). The Kyoto Protocol, an international treaty established by the United Nations in 1997, offers a framework for reducing greenhouse gas emissions and suggests solutions to climate change. Carbon credits, also referred to as carbon offset or emission reduction credits, are a measurement unit that represents the reduction, avoidance, or removal of greenhouse gas (GHG) emissions from the atmosphere (Wara and Victor, 2008) and carbon emission trading, a product of the Kyoto Protocol, aims to regulate emission levels, operating on the "cap and trade" principle, where countries are allocated a specific number of CO2 allowances based on their emission reduction targets. These countries can sell surplus carbon permits to others while staying within their emission limits (Al Sadawi et al., 2021). Across the globe, carbon emission trading systems have been fostered, encompassing regions such as North America, Europe and Asia. Over 40 countries and 20 sub-nations have either executed or are in the process of adopting carbon emissions trading mechanisms (Tuerk and Zelljadt, 2016). Numerous countries, including New Zealand, Finland and Brazil have set ambitious goals to eliminate their carbon emissions soon (Darby and Gerretsen, 2019).Carbon credits play a dual role as an incentive for reducing emissions and as a strategy to mitigate existing emissions.

However, the technology behind managing and trading digital carbon credits faces significant challenges such as manipulation and integrity issues (Al Sadawi et al., 2021). (Spash, 2010) highlights how corporations can manipulate trading offsets for financial gain, while (Schneider and La Hoz Theuer, 2019) points out that using different criteria to achieve climate mitigation targets and double counting emission reduction records are examples of how inadequate accounting can compromise environmental integrity.

One of the most prominent challenges is the widespread practice of double counting, where emission reduction records are counted multiple times, creating inflated perceptions of progress. Additionally, there is a crucial need for accurate price prediction mechanisms within the carbon market, as current price fluctuations hinder stakeholders' ability to make informed decisions and investments. Equally important is establishing a trusted marketplace, as concerns persist regarding manipulation and transparency, which undermines confidence in the system. Addressing these challenges is essential for ensuring the credibility and effectiveness of carbon credit initiatives in the fight against climate change.

To address these challenges, a multifaceted approach is necessary. This research advocates for enhanced transparency and accountability within carbon markets, coupled with the development of a blockchain-based platform. This platform serves to prevent double-counting issues and offers accurate price prediction mechanisms, in addition to functioning as a trading marketplace for carbon credits. Through the integration of such innovative technology, we aim to strengthen the integrity of carbon markets and foster confidence in carbon pricing as a viable tool for climate mitigation.

Blockchain technology offers compelling advantages over traditional systems, particularly in terms of applicability, scalability, computational costs, and energy consumption. Its decentralized nature enhances transparency and trust among participants, which is essential for carbon markets where multiple stakeholders interact. Blockchain supports smart contracts, which can automate verification and compliance processes, significantly reducing administrative costs and enhancing operational efficiency. Scalability is addressed through layered architectures and parallel processing capabilities, enabling high transaction volumes without sacrificing performance. In terms of computational costs, blockchain eliminates intermediaries, lowering transaction fees and operational overhead. Additionally, many modern blockchain systems employ energy-efficient consensus mechanisms, reducing the environmental impact associated with traditional networks. This combination of features makes blockchain a suitable choice for enhancing the efficiency and sustainability of carbon markets.

Implementing blockchain systems in carbon markets faces several practical challenges that can hinder their adoption. One of the primary concerns is the complexity of the technology, which may deter stakeholders unfamiliar with blockchain from engaging with it. Additionally, integrating blockchain with existing legacy systems can be technically challenging and costly, requiring significant investment in new infrastructure. Regulatory uncertainty also poses a significant barrier, as the legal framework surrounding blockchain and carbon markets is still evolving. Issues related to data privacy and protection further complicate matters, as the transparency of blockchain may conflict with the need for confidentiality in certain transactions. Lastly, ensuring data quality and verification processes is essential for maintaining the integrity of the carbon market, and establishing these mechanisms can be a considerable hurdle. However, it is important to note that these challenges do not apply to this research, as it focuses on innovative solutions that leverage blockchain technology to enhance transparency and integrity in carbon markets.

This chapter is structured as follows: section 1.2 provides the research statement,section 1.3 presents the research challenges, section 1.4 outlines the objective of this thesis, section 1.5 presents the significance of the thesis, section 1.6 outlines the plan of this thesis and finally, section 1.7 concludes the chapter.

1.2 Research Statement

In light of the growing importance of carbon credits in mitigating environmental impact, effective carbon credit management is pivotal. This section provides an overview of the challenges related to carbon credit management. Various approaches have been employed to advance the management of carbon credits, but the majority of these methods are built on a centralised architecture. Centralised carbon credit management systems often store critical information on a single platform, making them susceptible to issues such as manipulation and system failures, which can compromise the integrity and security of the entire carbon credit ecosystem.

Various issues have arisen concerning different facets of carbon credit management, such as trust and the clarity of environmental data. It is essential for carbon credit management systems to manage and handle data related to individuals' carbon footprints properly. Consequently, these systems must offer dependable methods for users to manage and trade their carbon credits effectively. Numerous studies suggest that blockchain technology could improve the management of carbon credits. The immutable nature of blockchain means that once data related to carbon credits is recorded, it cannot be changed. The decentralized structure of blockchain removes the need for a central authority. Furthermore, its traceability allows users to track any changes made to their carbon credit data. As a result, the adoption of blockchain technology enhances trust among users within the carbon credit management system.

This thesis aims to identify solutions to problems related to price prediction, the trading marketplace, double-counted credits, and effective carbon credits management.Specifically, it addresses the following research questions:

- How can we develop an intelligent, trustworthy, and global platform for managing and trading carbon credits?
- How can we develop an intelligent mechanism to counter the double counting of carbon credits?
- How can we intelligently and dynamically predict the price of carbon credits based on multiple factors?
- How can stakeholders reliably trade carbon credits through a secure and trustworthy marketplace?
- How can we validate the solutions developed for the above research questions?

It presents the initial effort to leverage smart contracts and blockchain to provide a trusted management and trading system for carbon credits. Additionally, it introduces an innovative approach, built on blockchain technology using smart contracts and machine learning models. This method predicts future carbon credit prices and detects duplicate entries, ensuring that no carbon credits are double counted.

1.3 Research challenges

Recent advancements in carbon credit management strategies, primarily driven by academic and business research, often rely on centralized systems. While these systems are efficient, they are susceptible to misuse, which poses challenges in creating a secure and dependable environment for carbon credit management. Despite the widespread interest in blockchain technology across various sectors, progress in the carbon credit management area has been modest. The decentralized nature of blockchain, which prevents any single entity from controlling the entire system, presents a viable solution to overcome the limitations of centralized approaches. This decentralized structure ensures secure and transparent transactions in carbon credit management. A comprehensive literature review has identified several key challenges and gaps in the existing research on carbon credit management:

Establishing a Trusted Marketplace: There is a critical need for a trusted marketplace built on blockchain technology. This entails integrating intelligent models to facilitate carbon credit transactions while upholding the privacy and security of these transactions in a trustworthy manner.

Double Counting Mitigation: Effectively addressing the issue of double counting in carbon credit transactions is paramount. An intelligent method is required to ensure the accuracy and integrity of the carbon credit accounting system, preventing discrepancies and maintaining the credibility of carbon credit transactions.

Future Price Prediction: Predicting the price of carbon credits is a key challenge. Implementing a method to forecast the price of carbon credits that leverages machine learning models is essential. This predictive capability enables stakeholders to make informed decisions regarding carbon credit investments and trading.

In a carbon credit trading platform, the integration of price prediction and double counting is a very powerful combination. Price prediction helps traders make informed buying or selling decisions by forecasting future credit prices, while double counting prevention ensures each carbon credit is only used once, maintaining the market's integrity. Together, these features enhance market efficiency, ensure regulatory compliance, and provide reliable data for strategic planning, making the platform more stable, trustworthy, and user-friendly for traders.

In this thesis, we propose, develop, and implement robust blockchain-based approaches for managing carbon credits, aiming to address the challenges identified in the current literature. These methods integrate blockchain technology, foundational principles of carbon credit management, and machine learning techniques to enhance the efficiency and reliability of the system.

1.4 The objective of this thesis

The primary aim of this thesis is to develop and evaluate intelligent methods using blockchain technology for carbon credit management. Understanding the importance of managing carbon credits in a secure and reliable environment is crucial. The thesis sets out to achieve the following objectives:

- to develop an intelligent global platform that reliably manages and trades carbon credits.
- to develop an intelligent system to prevent the double counting of carbon credits.
- to develop an intelligent approach to dynamically predict the price of carbon credits based on multiple factors.
- to develop mechanisms to enable the stakeholders to trade carbon credits in a reliable manner.
- to construct a prototype to assess the effectiveness of the proposed methods.

1.5 Significance of the Thesis

The application of blockchain technology in managing and trading carbon credits represents a significant advancement in enhancing carbon market performance and fostering trust among users. This thesis is pivotal in addressing the challenges identified in existing research by introducing innovative, blockchain-based approaches that leverage machine learning and smart contracts for effective carbon credit management and trading.

The impact of this thesis can be divided into two key dimensions: scientific and social contributions. From a scientific perspective, this research advances the fields of blockchain technology and machine learning within the context of environmental management, providing new insights and methodologies that can be applied to similar challenges in the future.

On the social front, the implementation of these intelligent systems aims to enhance the transparency, efficiency, and reliability of carbon credit markets. By doing so, it supports global efforts to mitigate climate change, empowering stakeholders with trustworthy tools to navigate the complexities of carbon trading and making a meaningful contribution to sustainable environmental practices.

1.5.1 Scientific contribution

This research makes the following scientific contributions:

- We develop an intelligent and global blockchain platform to manage carbon credits.
- We develop an intelligent mechanism to counter the double counting of carbon credits.
- We develop an intelligent approach to dynamically determine the price of carbon credits globally.
- We develop mechanisms to enable the stakeholders to trade carbon credits in a reliable manner.

1.5.2 social contribution

This research makes the following social contribution:

- Empowering stakeholders to engage in carbon credit trading represents a pivotal step towards sustainability. By facilitating the exchange of carbon credits, we not only encourage environmental responsibility but also contribute to the larger goal of mitigating climate change. This innovative approach enables stakeholders to actively participate in the carbon market, fostering a collective effort towards a greener and more sustainable future.

- Providing individuals with the capability to effectively manage, trade, and track their carbon credits is a transformative initiative with far-reaching implications. By enhancing accessibility and transparency in the carbon credit ecosystem, we empower people to take ownership of their environmental impact. This comprehensive system not only encourages responsible carbon management but also fosters a sense of accountability, as individuals actively contribute to the global mission of reducing carbon footprints.

- Addressing the challenge of double counting is a crucial stride in optimizing the efficiency of carbon credit systems. Through the implementation of robust mechanisms, we ensure the accurate accounting of carbon credits, mitigating the risk of duplication. By resolving this issue, we enhance the credibility and reliability of carbon credit programs, thereby reinforcing the integrity of carbon markets. This proactive measure aligns with our commitment to creating a more dependable and effective framework for carbon credit trading on a global scale.

1.6 Plan of the Thesis

In this thesis, we propose and develop a variety of models, services, and algorithms that support the implementation of a blockchain-based system for managing and trading carbon credits. The thesis is organised into eight chapters, as illustrated in Figure 1.1 A brief description of each chapter is as follows:

chapter 2 presents a systematic literature review on carbon credits trading and management using blockchain, aiming to establish that the addressed issues in this thesis are novel and not previously resolved in existing research.

chapter 3 clearly delineates the problems addressed in the thesis, derives research questions from these issues, and establishes specific research objectives.

chapter 4 outlines the research methodology, utilizing the design science research approach to tackle the gaps and deficiencies found in the existing literature. It also introduces the solution developed to meet research objective 1, which involves the creation of an IBMCC platform that integrates blockchain technology with carbon credits management. This chapter provides a thorough discussion of this platform.

chapter 5 provides details on the double counting sentry mechanism developed to solve the problem of double counting, thereby providing a comprehensive solution for research objective 2. Details of the workings of the prototype developed to answer this research question are demonstrated through screenshots and accompanied by explanations which are included in this chapter.

chapter 6 describes in detail the carbon credits market predictive dynamics a multi factorial price prediction model, which is designed to address research objective 3. This chapter includes the specifics of how the prototype operates to address this research question, with demonstrations provided through screenshots and accompanying explanations.

chapter 7 presents the green hub, the functionality of the marketplace and the trading mechanisms as a solution for objective 4, detailing how each component works within the system.

chapter 8 concludes the thesis by summarising its achievements and suggesting future avenues for study expansion.

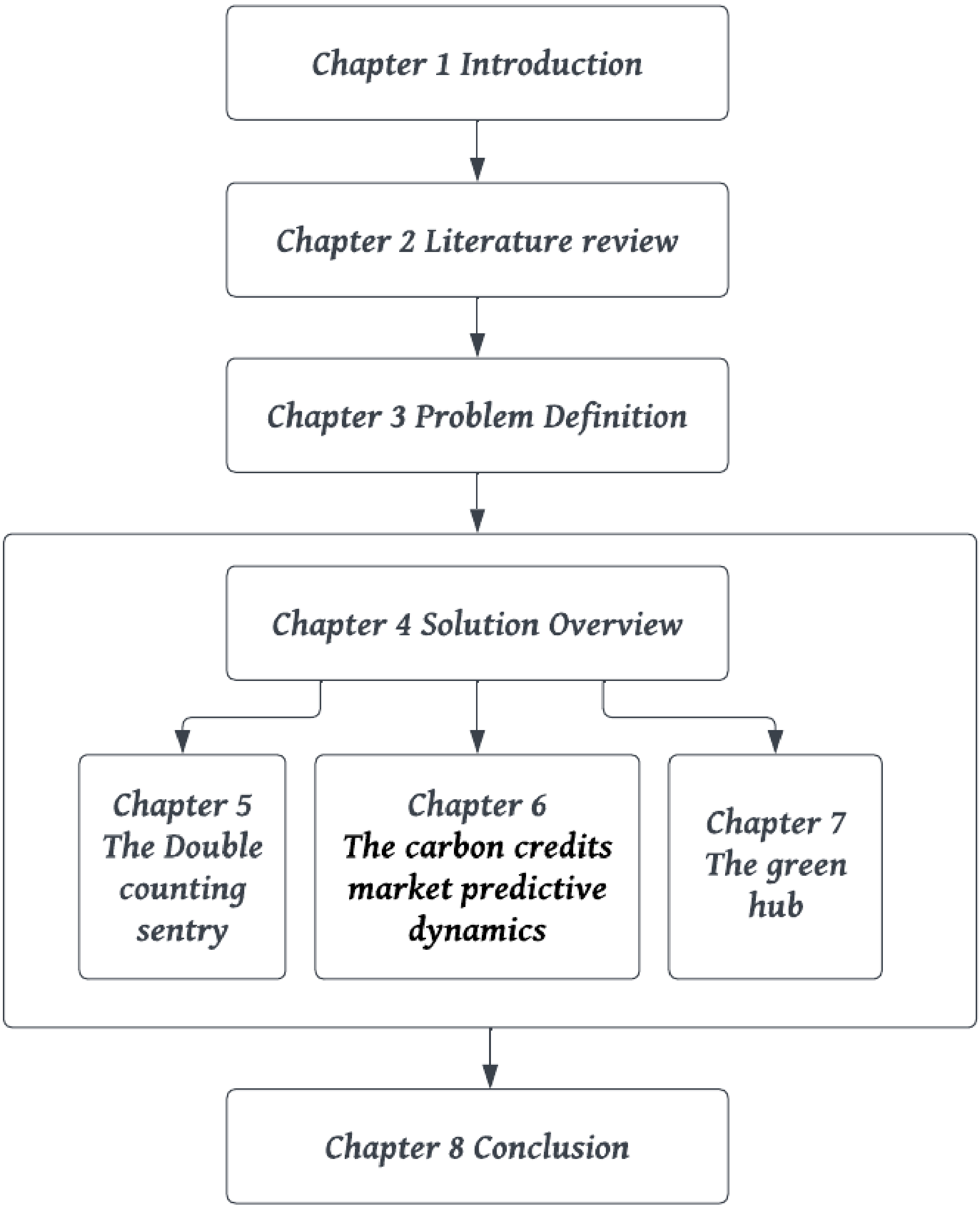

Figure 1.1 : The thesis structure

1.7 Conclusion

Blockchain technology is a rapidly evolving paradigm that encapsulates a diverse array of features, particularly focusing on establishing trust and transparency within a system. The decentralised nature of blockchain technology presents a distinctive opportunity to manage carbon credits effectively and reliably. The principal objective of this thesis is to develop solutions aimed at addressing significant issues related to carbon credit trading and management. which are identified in the current literature. This section delineates the specific issues under investigation in this thesis. The intelligent models developed for carbon credit trading and management aim to improve trust and transparency in transactions within the carbon market through the use of blockchain technology, machine learning, and smart contracts. The research problem is clearly articulated, and the thesis thoroughly examines the challenges inherent in existing carbon credit management processes. Additionally, the chapter explores the anticipated scientific and social contributions resulting from this research, with a specific focus on the realm of carbon credit management. A glimpse into the subsequent chapters is also provided.

In the following chapter, a systematic literature review. which analyses the pertinent studies in the field of carbon credit management is presented. The review underscores that the issues addressed in this research have not been adequately explored in prior studies, highlighting the novel contributions and insights expected from this thesis.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, a systematic literature review on the use of blockchain in carbon credits management is presented.

In this research, we propose a web-based platform that utilises the power of blockchain and AI to manage carbon credit trading. This system can monitor, track, and report carbon emissions and trading activities to eliminate the challenges and providesa highly transparent mechanism in the carbon trading market. Blockchain's increasing prominence has been observed in diverse areas, such as cryptocurrency trading and financial services. As a result, its potential application in the carbon credits market has become a crucial research topic. According to the Climate Chain Coalition, through consensus mechanisms and interoperability, implementing blockchain technology will boost confidence in the capital market and contribute to the goals of limiting climate change on a local and global scale. In relation to this matter, we conduct a systematic literature review (SLR) to uncover the gaps in the existing literature on managing and trading carbon credits using blockchain. The structure of the chapter is as follows: section 2 provides a background to the research components; section 3 presents the carbon credits management system features; section 4 outlines the procedure used to narrow down the papers to be included in this SLR, covering both the inclusion and exclusion criteria and the criteria for searching the literature; section 5 summarises all the shortlisted papers and section 6 concludes the SLR.

2.2 Background

This section presents the essential background knowledge required to understand this study's topic, including blockchain and carbon credits.

- Carbon Credits: Carbon credits represent a market-based strategy for combating climate change by incentivising the reduction of greenhouse gas emissions. They serve as a driving force for companies, organisations, and individuals to adopt cleaner and more sustainable practices that lead to a decrease in greenhouse gas emissions. A unit of measurement within this framework signifies the removal or avoidance of one metric ton of carbon dioxide (CO2) or its equivalent in other greenhouse gases from the atmosphere (Wara and Victor, 2008). The foundation of carbon credits lies in emission reduction projects spanning various sectors, including renewable energy, energy efficiency, reforestation, and waste management. These projects contribute to the reduction of greenhouse gas emissions. Independent third-party organisations verify and certify the emission reductions achieved by these initiatives. By adhering to recognised standards and methodologies, these organisations establish the credibility of the generated carbon credits. Following successful verification, carbon credits are allocated to the emission reduction projects. These credits then become commodities traded within the carbon market. This marketplace enables entities surpassing their emission reduction targets to sell their surplus credits, while those striving to meet targets can purchase credits to offset their emissions. Figure 2.1 illistrate the carbon credits trading mechanisam, This trading mechanism underscores commitment to environmental sustainability and offers financial backing for emission reduction projects.

  Carbon credits exist in distinct forms, encompassing voluntary and compliance credits. Individuals, companies, or organisations voluntarily purchase carbon

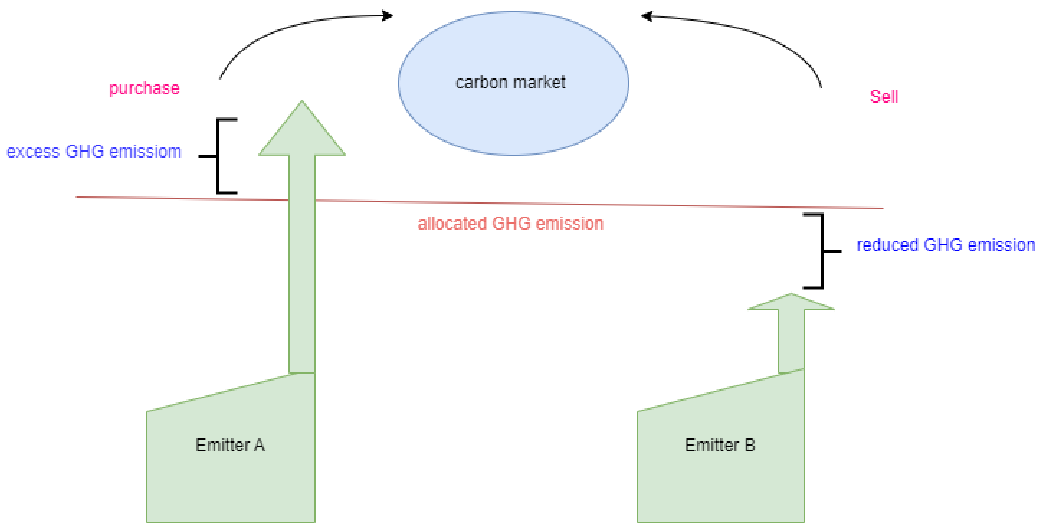

Figure 2.1 : How carbon credits work.

credits to offset emissions or exhibit environmental responsibility. Compliance carbon credits are used by companies to fulfil regulatory emission reduction obligations as mandated by governments or international agreements. Despite their potential benefits, carbon credits have encountered challenges, such as double-counting and project additionality concerns. Addressing these challenges necessitates robust regulations and transparent monitoring to ensure the effectiveness and legitimacy of carbon credits. A decentralised platform for managing and trading carbon emissions is imperative to surmount these challenges. The emergence of blockchain technology offers a transparent and reliable management system capable of restoring faith in the carbon credit ecosystem.

(Perdan and Azapagic, 2011) state that carbon trading is a market-based tool designed to combat climate change by trading emissions from six key greenhouse gas emissions. These carbon credits are authorised to emit a specific quantity of carbon dioxide or other greenhouse gases, which is known as a carbon credit. One credit allows for one tonne of carbon dioxide emission or another greenhouse gas equivalent(Kenton, 2019)

- Blockchain: As defined by (Crosby et al., 2016), blockchain functions as a public ledger documenting all executed transactions or digital events shared among relevant parties. Consensus among a majority of system users is required for every transaction to be recorded in this public ledger. Once entered, information cannot be erased. Each transaction is preserved in a specific verifiable record on the blockchain. Originally conceived as the foundational technology for the cryptocurrency Bitcoin, blockchain has evolved into a secure and versatile distributed ledger system applicable beyond the realm of cryptocurrencies. Operating as a decentralised, immutable, and transparent digital ledger, the blockchain maintains a chronological and sequential record of transactions through a network of computers referred to as nodes. Each node holds a complete copy of the ledger, and consensus among the majority of nodes is required for any alterations or additions, ensuring the security and integrity of data. Nonetheless, the successful integration and widespread acceptance of blockchain applications hinge on addressing technical, social, and regulatory challenges in the evolving landscape of this groundbreaking technology. The attributes of blockchain, including decentralisation, distribution, security, transparency, automation, traceability, privacy, and reliability, play a pivotal role in the value enhancement of carbon trading markets. These attributes have benefited carbon trading and hold potential for future advancements in this arena (Al Sadawi et al., 2021).

2.3 Key requirements from a blockchain platform for carbon credits management.

This section discusses the factors to be considered in the carbon credits management system that will form the basis for comparing the existing studies in the

SLR. An overview and a discussion on the importance of each feature we consider essential to the carbon credits management system are given in the following.

2.3.1 The ability to establish the provenance of carbon credits. (R1)

In the context of this study, provenance refers to the origin or source of carbon credits. It is crucial to ensure the legitimacy and authenticity of credits. Since carbon credits are apparent evidence of efforts to reduce emissions, it is essential that they can be attributed to real, significant initiatives. In the world of carbon credits, provenance is paramount as it guarantees that emission reductions are genuine and achieved through verifiable and sustainable means. Robust provenance mechanisms provide transparency, accurate accounting, and reliable reporting, enabling businesses, governments, and individuals to make informed choices in offsetting their carbon footprints.(Wang et al., 2020) state that the potential for blockchain technology to establish the provenance of carbon credits has generated considerable interest. It provides an exceptional framework for preserving the complete life cycle of each carbon credit, from production to retirement, owing to its decentralised and irreversible nature. By establishing the provenance of carbon credits, we can build a robust and effective carbon market that is pivotal in advancing global climate action and environmental sustainability. Through provenance mechanisms, carbon credits can be tracked and verified, enabling buyers to ensure they purchase legitimate emissions reductions.

2.3.2 The ability to prevent double counting. (R2)

One of the most critical challenges in the realm of carbon credits is the problem of double counting. This issue arises when the same carbon or emission reduction is counted multiple times (Schneider and La Hoz Theuer, 2019), leading to inaccuracies and weakening market efficiency. Double counting undermines confidence in the carbon market and discourages participation from investors and businesses. It creates opacity and erodes trust in the legitimacy of claims concerning emission reductions. To counteract the double-counting problem, we need a trusted provenance mechanism that guarantees the transparency and authenticity of the carbon credit. An innovative solution emerges in the form of smart contracts. Smart contracts are pre-programmed agreements that are automatically executed when specific conditions are met(Kirli et al., 2022).

(NB, 2023) stated that the blockchain ledger guarantees the authenticity and transparency of carbon emissions data, offering a secure and effective approach to mitigate carbon emissions. In the same context, (Wang et al., 2020) highlights that blockchain can serve as a practical tool for directly storing, monitoring, tracking, and managing carbon emissions from participants across the entire life cycle within a supply chain network. Implementing such mechanisms within carbon markets is vital to eradicate the issue of double counting.

2.3.3 The ability to predict the future price of carbon credits.(R3)

Price volatility in carbon markets presents a significant pricing problem that stems from the fluctuation of carbon credit prices over short periods of time. This volatility makes it challenging for market participants, including governments, companies, investors, and environmental organisations, to accurately predict and manage the financial implications of their emissions reduction strategies. Using machine learning to predict carbon credit prices is a potential solution to address price volatility in carbon markets. Machine learning techniques leverage historical data and various factors to build predictive models that can provide insights into future price movements. Predicting the future price of carbon credits can offer several benefits to different stakeholders and industries. Accident price predictions are crucial for entities participating in carbon trading and offset projects. It helps them decide when to buy or sell carbon credits, maximising their gains or minimising losses.

Companies and governments can use price forecasts to design better emission reduction strategies. By knowing the expected price of carbon credits in the future, they can prioritise investments in cleaner technologies and renewable energy sources, making their operations more sustainable and cost-effective.

2.3.4 The ability to build a marketplace to allow the trading of carbon credits.(R4)

The carbon credit marketplace is a system designed to facilitate the trading and exchange of carbon credits. An effective marketplace promotes participation from a broad spectrum of competitors, including large organisations, smaller enterprises, and even individual carbon credit holders. Moreover, the marketplace improves the simplicity and effectiveness of transactions by developing a platform where buyers and sellers can trade carbon credits. These four features form the basis of our investigation into the existing systems discussed in the literature to determine if they offer a solution to address the aforementioned issues in the carbon market. The following section details the method used to shortlist the papers in the SLR.

2.4 The process used to shortlist the papers chosen for this SLR:

This section explains the various steps used to identify the relevant papers that are selected for this SLR, following the guidelines presented by (Kitchenham et al., 2009).

We utilized the following four-step procedure:

- Step 1: Process for searching the literature: This step involves defining the search terms and identifying the data sources, and the process of data collection.

- Step 2: Criteria for inclusion and exclusion: Specific criteria are established to direct the extraction of the most pertinent studies.
- Step 3: Quality assessment: Two quality evaluation standards are used to assess each article or journal paper.
- Step 4: Data analysis: Data are collected and documented after the selected research paper has been analysed.

2.4.1 Step 1: Process for searching the literature

The first step in the SLR is to identify the primary data sources and define the search terms and the search procedures used to identify the relevant studies in the existing literature that focus on the management and trading of carbon credits. The details of this step are as follows:

Identify the databases:

The electronic scientific database selected to source the relevant papers for the SLR are listed in Table 2.1. Searching these databases will ensure that the appropriate papers from the literature are identified to achieve the goal of this SLR.

Identifying the search terms:

To search the databases for relevant literature, a number of key terms were used which were extracted from the research questions, as shown in Table 2.2. The final search term was constructed using Boolean" AND" to combine keywords, Boolean "AND" to combine keywords, Boolean "OR" when there were many similar keywords and quotation marks were used in the search query to capture the relevant texts from the literature as follows: ((Blockchain OR "Distributed Ledger Technology" OR "Smart contract") AND ("Carbon Cred- its" OR "Carbon Trading" OR

Database	URL
1. IEEE Explore	https://www.ieee.org/
2. Springer Link	https://link.springer.com/
3. A C M	https://dl.acm.org/
4. Scopus	https://www.scopus.com/home.uri/
5. Web of Science	https://login.webofknowledge.com/
6. Science Direct	https://www.sciencedirect.com/
7. Google Scholar	https://scholar.google.com/

Table 2.1 : Databases and the URL for each database.

Blockchain	Distributed ledger technology, smart contract, DLT
Carbon credits	credits carbon emission, carbon certificate, carbon trading,carbon money,

Table 2.2 : Research terms

"Carbon emissions" OR "Carbon Money")). We also used another research term (blockchain AND carbon credits) to widen the search.

Information required from the selected papers:

Specific information is required for each record, namely the title, abstract, and full text. as shown in Figure 2.2 104 studies were found after searching the databases. 16 articles were excluded because they were duplicates. The remaining 86 articles underwent the following filtration stages.

Publication date:

A paper had to be published between 2019 and 2023 to be eligible for the SLR. This is because, prior to this, not much research had been conducted on the use

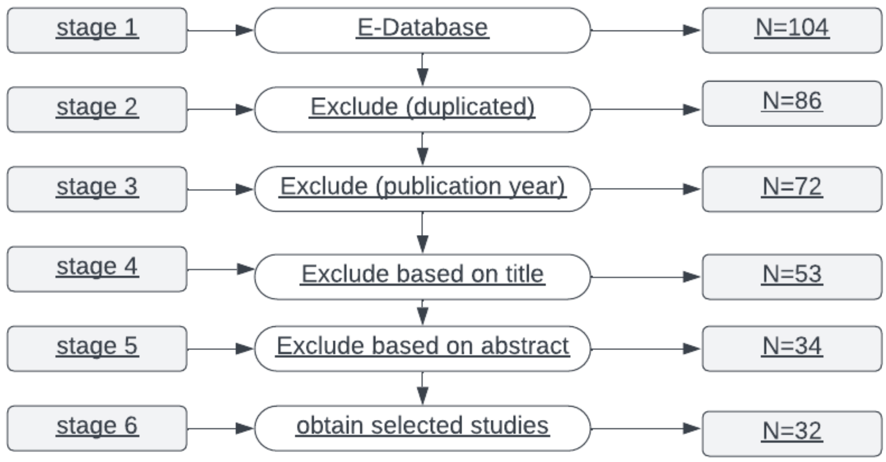

Figure 2.2 : SLR selection process.

of blockchain technology with carbon credits. Some papers were eliminated based on their publication date, which reduced the number of papers to 72 studies. The remaining publications were subject to further inclusion and exclusion criteria, as detailed in the next step.

2.4.2 Step 2: Defining the inclusion and exclusion criteria

This step details the inclusion and exclusion criteria that were used to guide the selection of the most relevant papers. The details of this step are as follows:

Paper selection criteria:

The initial search results were subjected to the following inclusion and exclusion criteria to identify whether the paper should be included in or excluded from the SLR. **Inclusion criteria:** For a paper to be included in the SLR, it needs to meet the following inclusion criteria:

- Criterion : The paper must be relevant to blockchain and carbon credits .
- Criterion : The paper is written in English and the full text is available.

- Criterion : It must be a conference or journal paper.

Exclusion criteria: A paper is excluded from the SLR process if it meets the following criteria:

1. • It is a duplicate paper.
2. • It was published before 2019.

Article selection procedure:

As a result of applying the publication date-based inclusion criteria and removing the duplicated papers in the previous step, the total number of articles decreased from 104 to 72. Then, the filtration process began. The title of all 72 studies were read in the first phase and irrelevant papers were eliminated. If it was unclear whether the article was relevant judging from its title, it advanced to the second stage. As a consequence, 53 studies moved to the next phase. The second filtration stage involved reading the abstracts of the papers, and those that suited the study's goal advanced to the third stage. As a result, 35 articles moved to the third stage. The third stage involved reviewing the full texts of the 35 papers that had been shortlisted. Only 34 were determined to be pertinent to our research topic. The stages of evaluating and selecting the relevant papers for the SLR are summarised in Table 2.3.

2.4.3 Step 3: Quality evaluation.

In this step, three quality Assessment criteria (QA.1 to QA.3) were developed and applied to review each selected article. Table 2.4 presents the quality assessment criteria used to assess each shortlisted article. The 34 selected papers were retrieved and critically evaluated based on the quality evaluation questions as follows:

Filtration Stage	Method	Assessment Criteria
1st Filtration	Identify the related studies from the online databases based on the title.	If the title contains keywords, Yes=include, No=exclude
2nd Filtration	Exclude studies based on the abstract.	If the abstract contains keywords Yes=include, No=exclude
3rd Filtration	Exclude studies based on the full text.	If the full text shows the study is relevant, Yes=include No=exclude

Table 2.3 : Filtration stages

QA.1	Is the paper research-based?
QA.2	Is the aim of the study clearly stated?
QA.3	Does the paper provide clear evidence of the finding?

Table 2.4 : Quality assessment criteria used to assess each shortlisted article

2.4.4 Step 4: Data analysis(papers shortlisted for the SLR and their broad areas of research).

Based on the quality assessment criteria, only 28 articles were shortlisted and included in the SLR. Information on these papers is provided in Table 2.5. The papers that fall under each area of research are discussed.

No	Study title	Year	Author	Area of Research
1	Application of blockchain and IoT in cap and trade of carbon emissions	2023	Thirunavukkarasu et al.	Carbon management
2	Smart contract design and process optimisation of carbon trading based on blockchain: The case of China's electric power sector	2023	Zhang et al.	Carbon trading
3	A Blockchain-based decentralised framework for carbon accounting, trading and governance	2022	Rawat et al.	Carbon trading
4	Carboncoin: blockchain tokenization of carbon emissions with ESG-based Reputation	2022	Golding et al.	Carbon trading +reputation

No	Study title	Year	Author	Area of Research
5	STRICTs: A Blockchain-enabled smart emission cap restrictive and carbon permit trading system	2022	Lu et al.	Carbon trading
6	A European emissions trading system powered by distributed ledger technology: An evaluation framework	2022	Mandaroux et al.	Carbon trading
7	Construction of carbon trading platform using sovereignty blockchain.	2020	Bai et al.	Carbon trading
8	A permissioned blockchain enabled trustworthy and incentivised emission trading system	2022	Muzumdar et al.	Carbon trading
9	Transparency in Carbon Credit by Automating Data-Management Using Blockchain	2022	Chakraborty et al.	Carbon management

No	Study title	Year	Author	Area of Research
10	Bringing technological transparency to tenebrous Markets: The Case for using blockchain to validate carbon credit trading markets	2022	Marchant et al.	Carbon management
11	Simulation research on carbon emissions trading based on Blockchain	2022	Zhou &Zhang	Carbon trading
12	Blockchain-enhanced trading systems for construction industry to control carbon emissions	2022	Shu et al.	Carbon management
13	A comprehensive hierarchical blockchain system for carbon emission trading utilising Blockchain of things and smart contract	2021	Al Sadawi et al.	Carbon trading
14	Carbon emission monitoring and credit trading: the blockchain and IOT approach	2021	Effah et al	Carbon management

No	Study title	Year	Author	Area of Research
15	Application and research of Carbon Asset Management Based on Blockchain	2021	Li & Li	Carbon management
16	Blockchain-based carbon trading mechanism to elevate governance and smartness	2021	Al Sadawi & Ndiaye	Carbon trading
17	Blockchain-based carbon allowance trading market construction	2021	Yuan et al.	Carbon trading
18	Emission trading innovation mechanism based on Blockchain	2021	Zhao et al.	Carbon trading
19	Design of a double-blockchain structured carbon emission trading scheme with reputation	2019	Liang et al.	Carbon trading +reputation
20	Carbon Credits on Blockchain	2020	Patel et al.	Carbon trading
21	A hierarchical blockchain of things network for unified carbon emission trading (HBUETS): A conceptual framework	2020	Al Sadawi et al.	Carbon trading

No	Study title	Year	Author	Area of Research
22	Applying blockchain to the Australian carbon market	2020	Hartmann & Thomas	Carbon trading
23	Carbon trading with Blockchain	2020	Richardson & Xu	Carbon trading
24	Blockchain of carbon trading for UN sustainable development goals	2020	Kim & Huh	Carbon management
25	Designing a blockchain model for the Paris agreement's carbon market mechanism	2020	Franke et al.	Carbon trading
26	Research on model of blockchain-enabled power carbon emission trade considering credit scoring mechanism	2019	Cui et al.	Carbon trading
27	A Reputation-based carbon emissions trading scheme enabled by Blockchain	2019	Wang et al.	Carbon trading +reputation
28	A blockchain-based peer-to-peer trading scheme coupling energy and carbon markets	2019	Hua & Sun	Carbon trading

No	Study title	Year	Author	Area of Research

Table 2.5 : The shortlisted articles included in the SLR.

2.5 Discussion of the papers shortlisted for the SLR by research area.

Each shortlisted paper was analysed based on its scope, area of research, author and summary of its research question. Based on the analysis, the selected articles were divided into the following two broad topic areas:

2.5.1 Carbon credit/emission management:

Several topics can be explored under this general research area. One of the most prominent areas is the integration of blockchain for emissions monitoring and management. (Thirunavukkarasu et al., 2023) and (Chakraborty et al., 2022) both propose the use of blockchain technology to automate data collection and ensure transparency in managing carbon credits. They focus on integrating data into the blockchain for emissions monitoring and establishing a carbon cap and trade system. The use of sensors for accurate data collection is emphasised.

Another important area is developing blockchain-based IoT frameworks for emission monitoring. (Effah et al., 2021) introduce a blockchain-based IoT framework for carbon emission monitoring and credit trading. The system is not hampered by any form of human interference in the reporting of emission data by companies and the recording of carbon emission data, which can overcome many of the challenges associated with carbon trading, such as double counting, corruption, and transparency issues. This framework aims to improve accuracy, transparency, and autonomy in reporting emission data. Smart contracts and incentive mechanisms on the blockchain are utilised for efficient and fair carbon credit trading.

The research area of blockchain-based carbon emission rights verification was also studied.(Kim and Huh, 2020) proposed a governance system analysis and the use of a blockchain mainnet engine to learn proven data further. This system can help make transactions more reliable and can be used to measure and verify carbon emission rights, which is essential in carbon trading. Using blockchain technology, this system can provide a secure and transparent way to verify carbon emission rights, which can help reduce fraud and increase trust in the carbon trading market.

(Marchant et al., 2022) proposed the use of blockchain to address the problems associated with carbon credit trading markets. The paper suggests that adopting Blockchain technology and smart contracts can provide more robust protections and greater transparency to carbon credit markets, which can help build trust and increase the effectiveness of carbon credits in mitigating climate change. The paper also emphasises the need for more active measures to solve the double counting problem and enforce the basic underpinnings of the contracts used in carbon credit trading markets.

(Shu et al., 2022) studied the area of decentralised emissions-trading systems and proposed an emissions-trading system that handles carbon emissions in both a construction project's operation and materialisation phases. The proposed system is powered by blockchain technology under the Industry 4.0 framework, which makes it decentralised, open, and autonomous. The proposed system offers substantial incentives to low-carbon entities, improving the system's effectiveness.

(Li and Li, 2021) investigated the use of blockchain for carbon asset management to assess the potential of blockchain technology in improving the credibility and efficiency of carbon asset management in the case of the carbon market in China. The study focuses on creating a credible and transparent trading environment.

2.5.2 Carbon trading:

The selected papers' explorations of carbon trading can be divided into many general research areas.(Mandaroux et al., 2021) explored blockchain technology and smart contracts for carbon credits trading and developed a comprehensive framework that utilises blockchain technology in conjunction with the European Union Emissions Trading Scheme. This framework aims to enhance transparency and traceability in the carbon credit trading process, providing a foundation for better data management and governance. (Al Sadawi et al., 2020) proposed a framework that makes use of smart contracts in the Blockchain of Things to ensure system integrity and achieve fair trade status that prioritises the environment over cost savings and profit-making for businesses. In the same research area, (Al Sadawi and Ndiaye, 2021) present a blockchain-based carbon emission trading mechanism that utilises smart contracts and Ethereum blockchain to address the challenges of the current carbon emission trading scheme. By leveraging blockchain technology's decentralisation, security, traceability, immutability, and privacy, this system aims to elevate the governance and smartness of carbon trading.

Additionally, (Muzumdar et al., 2022) leveraged Hyperledger blockchain technology and smart contracts to build a secure and trustworthy emissions trading system. The proposed system addresses monitoring, verification, and transparency issues while introducing a priority-based auction mechanism for fair carbon credit trading.

(Zhao et al., 2021) explored the application of Hyperledger Fabric as a blockchain platform for emissions trading. They emphasised the coordination and integration of different technologies to design innovative emissions trading mechanisms. This approach enhances transparency and traceability.

(Patel et al., 2020) proposed a blockchain solution for trading carbon credits, emphasising decentralisation, transparency, and immutability. Their approach simplifies the trading process which becomes more cost effective as more participants join the network. It promotes the use of blockchain technology to track and verify carbon credits.

Another important area of study is the efficiency and transparency of carbon trading systems: (Zhang et al., 2023) introduced a blockchain-based smart carbon trading system designed for the Chinese power market. Their study highlights the importance of managing high-quality carbon data for measurable and verifiable emission reductions. This system incorporates a bilateral pricing model, considering the costs for both buyers and sellers in carbon market transactions. (Hartmann and Thomas, 2020) explored the potential of blockchain technology to improve the Australian carbon market's efficiency, equity, and effectiveness.

(Richardson and Xu, 2020) proposed a permissioned blockchain system for emissions trading, building on the success of the European Union Emissions Trading Scheme. Their approach increases efficiency, transparency, and liquidity in carbon trading.

(Rawat et al., 2022) presented a blockchain-based solution for trading carbon credits, emphasising decentralisation and a trustless environment. The proposed framework includes smart contracts to create a transparent and efficient carbon accounting, trading, and governance system. (Franke et al., 2020) contributed to carbon trading by examining the suitability of using blockchain technology to enhance the transparency and environmental integrity of the certificates generated by the Article 6.2 mechanism of the Paris Agreement. The study compared the suitability of two different blockchain platforms, Ethereum and Hyperledger Fabric, and provided a detailed analysis of the technical and political requirements.

Another area that attracts research attention is innovative approaches to emissions reduction and carbon trading, (Lu et al., 2022) proposed a blockchain-enabled system called STRICTs for carbon permit trading in the transport sector. This system aims to increase efficiency and reduce operational overheads while ensuring the reliability and correctness of data on carbon emissions and permits. (Yuan et al., 2021) introduced a carbon allowance trading scheme based on blockchain technology to promote carbon emission reduction. Users can buy and sell carbon quotas on the platform, and blockchain technology ensures security and transparency in all transactions. (Bai et al., 2020) utilised the sovereign blockchain model to build a platform for managing carbon credits and ensuring transparency and accountability in carbon trading. This sovereign blockchain approach introduces a novel perspective on how blockchain technology can enhance carbon credit management. (Zhou and Zhang, 2022) conducted a quantitative analysis of the application of blockchain technology in carbon emissions trading. They established a blockchain-based carbon emissions trading system, emphasising benefits such as automated authentication, traceability, data openness, and smart contract functionality.(Hua and Sun, 2019) proposed a blockchain-based peer-to-peer trading scheme that couples energy and carbon markets to address various challenges, including energy and carbon reduction imbalances, and residential privacy leakage. This innovative scheme offers a decentralised approach to trading energy and carbon allowances, promoting cost reductions and carbon emissions reductions.(Cui et al., 2019) proposed an annotative blockchain-enabled power carbon emission trade model that considers a credit scoring mechanism to ensure fairness and transparency in the carbon emission trading process. Blockchain technology and smart contracts ensure the secure and transparent storage and exchange of carbon credits.

2.5.3 Considering reputation in carbon trading:

(Golding et al., 2022) proposed a new design for blockchain-based carbon trading that eliminates the need for off-chain permits and introduces a decentralised approach to carbon emission trading. The proposed design incorporates ESG data to provide a more comprehensive reputation score for market participants. Carboncoin,

a more reliable application of carbon trading is made possible by a fungible asset that is automatically expensed through a blockchain certification process whenever ecologically costly energy is reported. This eliminates the need to deal with centralised alternatives in a politically divisive market.

(Wang et al., 2019) proposed a new carbon emissions trading scheme called BCR-CETS, which utilises blockchain technology and a reputation-based incentive mechanism to promote long-term carbon emissions reduction. It improves on previous models by introducing a calculation formula for the reputation value and demonstrating through case studies that the introduction of reputation is more beneficial for long-term carbon emissions reduction. In the same context, (Liang et al., 2019) presents a reputation-based transaction fee mechanism in the carbon emission trading market. The mechanism incentivises enterprises to invest in emission reduction by varying the transaction fees they must pay extra depending on their reputation value. Reputation reflects the comprehensive evaluation of enterprises' past emission reduction performance, which compares current and initial carbon emissions. Through this comparison, the percentage of emission reduction is calculated and converted into reputation. The proposed mechanism aims to improve ETS's efficiency, ensure the system's security and privacy, urge enterprises to improve their reputation, and ultimately promote emission reduction in society. introduced a transaction fee system in the carbon emission trading market that is based on reputation. By adjusting the additional transaction fees that businesses must pay based on their reputation value, the mechanism encourages businesses to invest in emission reduction. Reputation is based on a thorough analysis of an organization's historical record in reducing emissions by comparing its initial carbon emissions with its current emissions. The comparison allows for the calculation and conversion of the emission reduction percentage into reputation. By enhancing ETS's efficiency and guaranteeing its security and privacy, the suggested mechanism seeks to encourage businesses to enhance their reputations and, in the end, encourage society's reduction of emissions.

2.5.4 Related work:

A number of researchers have undertaken literature reviews in the area of blockchain and carbon credits. A study by (Chen, 2023) provides an overview of carbon credit markets, including compliance and voluntary markets, and discusses the challenges and opportunities associated with these markets. It also explores the role of carbon offsets in achieving net-zero emissions and the potential of forests as carbon sinks. The study suggests that there are concerns about the validity of carbon credits and that there is a need to improve the quality of carbon markets. Similarly,(Vilkov and Tian, 2023) investigated the scope and purpose of blockchain technology in carbon markets, specifically in emission trading schemes and carbon offset projects. They discuss several proposed marketplaces for carbon trading using blockchain technology. In the same context, (Francisco et al., 2022) analysed the state-of-the-art blockchain-based solutions applied to the carbon trading context and answered research questions related to the main advantages, current state, market opportunities, and challenges of using blockchain in carbon trading systems.(Sipthorpe et al., 2022) reviewed blockchain solutions for carbon markets, identified the current issues facing them, and determined the niches that blockchain technology could fill to improve them. They highlighted critical problems around scalability, systems integration, and regulation that must be overcome. A review by (Woo et al., 2021) explores the potential of blockchain technology in building energy performance measurement, reporting, and verification (MRV) and the carbon credit market.

2.6 Analysis of selected papers against the requirements :

Table 2.6 presents an analysis of the selected studies that address the challenges associated with carbon credit management, focusing on their methodologies and how they meet specific system requirements. Each study is evaluated against the following requirements: R1 (Requirement 1:The ability to establish the provenance of carbon credits), R2 (Requirement 2:The ability to prevent double counting), R3 (Requirement 3:The ability to predict the future price of carbon credits), and R4 (Requirement 4:The ability to build a marketplace to allow the trading of carbon credits.)

Study	Author	R1	R2	R3	R4
1	Thirunavukkarasu et al.				
2	Zhang et al.				
3	Rawat et al.	/			
4	Golding et al.				
5	Lu et al.	/			
6	Mandaroux et al.				
7	Bai et al.				
8	Muzumdar et al.				
9	Chakraborty et al.				
10	Marchant et al.	/			
11	Zhou &Zhang				

Study	Author	R1	R2	R3	R4
12	Shu et al.	/			
13	Al Sadawi et al.	/			
14	Effah et al.	/			
15	Li &Li	/			
16	AL Sadawi & Ndiaye	/			
17	Yuan et al.				
18	Zhao et al.	/			
19	Liang et al.				
20	Patel et al.				
21	Al Sadawi et al.				
22	Hartmann & Thomas	/			
23	Richardson & Xu	/			
24	Kim & Huh				
25	Franke et al.				
26	Cui et al.				
27	Wang et al.				
28	Hua & Sun				

Table 2.6 : Analysis of selected papers against the requirements

The analysis of the selected studies reveals that diverse methodologies have been employed, each providing unique insights into the effective management and trading of carbon credits. By systematically categorizing these studies according to the specified requirements (R1-R4), we gain a comprehensive understanding of their approaches to the carbon credit issue. This systematic evaluation highlights the implications of these methodologies for future research and practical applications in the field of carbon credit management.

2.7 The research gaps in the existing studies:

- **A provenance mechanism for carbon credits.**

  A review of the literature shows that several studies highlight the need for a provenance mechanism, while others propose an approach to prove carbon credits. For example, (Rawat et al., 2022) proposed a solution that includes a distributed ledger register for stakeholders, creating a provenance mechanism for carbon credits.

  Similarly, (Marchant et al., 2022) also suggested that integrating blockchain technology can provide a provenance mechanism by enabling traceability or monitoring after a transaction has been completed. (Al Sadawi et al., 2021) showed that the mechanism also provides transparency and traceability in the carbon trading market.

  (Effah et al., 2021) proposed a provenance mechanism for carbon emission data recording and reporting, which utilises the blockchain network's transparency and immutability to ensure the data's accuracy and traceability. Similarly, (Li and Li, 2021) proposed a provenance mechanism based on blockchain technology that provides full traceability of carbon assets and ensures the credibility of carbon asset transactions. In the same context, (Al Sadawi and Ndiaye, 2021) proposed a provenance mechanism that utilises blockchain technology to ensure the traceability and transparency of carbon emission trading. (Zhao et al., 2021) proposed a provenance mechanism based on blockchain technology, which can ensure the traceability and authenticity of carbon credits.

  (Lu et al., 2022) proposed a provenance mechanism in STRICTs to guarantee the reliability and correctness of the data.(Shu et al., 2022) proposed a system that uses a provenance mechanism to track the origin and history of carbon credits. The mechanism ensures the integrity of carbon allowance trading by utilising smart contracts. It tracks the source and ownership of carbon credits, ensuring that they are not double-counted or fraudulently created. (Hartmann and Thomas, 2020) proposed a provenance mechanism for carbon credits by recording the history of each credit on the blockchain. Similar to this, (Richardson and Xu, 2020) proposed a provenance mechanism that was designed to track the origin and history of carbon credits on the blockchain. This is achieved through smart contracts that record carbon credits issuance, transfer, and retirement and verify and approve carbon-reducing projects.

- **A mechanism to prevent double counting.**

  (Marchant et al., 2022) suggested that integrating blockchain and smart contracts into the market makes the double counting problem a non-issue by automatically retiring a credit once purchased or later claimed for a regulatory or other purpose. Blockchain technology can provide a solution to the double-counting problem in carbon credit trading markets. By integrating blockchain into these markets, carbon offset credits can be effectively tracked from creation to retirement, and every credit traded comes with a log that is immutable and follows it throughout its lifecycle. (Effah et al., 2021) suggests a blockchain-based monitoring system that can prevent double counting issues through its decentralised and transparent nature. (Al Sadawi and Ndiaye, 2021) proposed a blockchain-based carbon emission trading mechanism that uses smart contracts and Ethereum blockchain to help prevent the double spending of CO2 emissions allowances.

  While many researchers have highlighted the pivotal importance of tackling the double counting issue, it is striking that most of these initiatives have stagnated at the proposal stage, lacking subsequent phases of implementation, testing, or rigorous evaluation. This prevailing trend raises concerns about the practical applicability and real-world effectiveness of the proposed solutions. Furthermore, a critical observation derived from the reviewed literature is the conspicuous absence of any studies that have introduced a proactive methodology to prevent the occurrence of double counting. The absence of such preventive measures indicates a critical gap in current research efforts, signalling the need for comprehensive exploration and innovation in developing strategies that not only identify but also preclude instances of double counting in various contexts, particularly within the realms of environmental accounting and sustainability reporting. Bridging this gap is imperative for advancing carbon accounting practices' credibility and reliability and fortifying emissions reduction initiatives' integrity across diverse sectors. Future research should thus prioritize the formulation and testing of preventative measures, contributing not only to theoretical advancements but also to the practical implementation of robust solutions in real-world scenarios.

- **A mechanism to predict the future price of carbon credits.** (Zhang et al., 2023) described a bilateral pricing model for carbon trading. (Zhou and Zhang, 2022) discussed the pricing method used in blockchain-based carbon emissions trading simulation. The market mechanism forms the quota price, updated in units of one-time steps. The buying and selling quotations are adjusted based on the expected price. It is evident from the comprehensive review of the existing literature that none of the studies examined has put forward or elucidated any method or mechanism for intelligently predicting the price of carbon based on multiple factors. This notable gap in the research landscape underscores the need for the further exploration and the development of innovative approaches to enhance our understanding and forecasting capabilities in the dynamic realm of carbon pricing. Addressing this void in the literature can significantly contribute to the advancement of effective strategies for navigating the complexities of carbon markets and fostering sustainable practices. Future research endeavours should thus focus on bridging this gap, employing cutting-edge methodologies and analytical tools to develop robust models that can intelligently forecast carbon prices, thereby aiding stakeholders in making informed decisions in the evolving landscape of environmental economics.

- **A marketplace to enable the trading of carbon credits.** (Yuan et al., 2021) proposed a carbon allowance trading scheme as a marketplace for carbon trading. Also, (Zhao et al., 2021) suggested the establishment of a carbon trading marketplace based on blockchain technology, which can provide a transparent and efficient trading platform for carbon credits.

  The literature under examination exclusively put forword systems and mechanisms for carbon trading; notably, none introduced a dedicated trading marketplace for carbon credits, which was built with a mechanism to prevent double counting and a mechanism to predict future prices of carbon credits. Such a marketplace is crucial for ensuring a robust, transparent, and reliable environment for trading operations. The absence of a dedicated marketplace underscores the need for research and development in creating a specialized platform that not only facilitates carbon credit transactions but also adheres to high standards of strength, transparency, and dependability. In addressing this gap, future endeavors should prioritize the conceptualization and implementation of a purpose-built trading marketplace to optimize the efficiency and credibility of carbon credit trading.

2.8 Conclusion

In conclusion, this chapter has comprehensively reviewed the existing literature in the realm of managing and trading carbon credits. By categorising the body of work into two distinct areas, namely the trading and management of carbon credits, we have gained a nuanced understanding of the advancements and challenges in this critical field.

This systematic literature review outlines four essential criteria for a blockchain platform for managing carbon credits.

In the next chapter, we explore the gaps identified by the literature review. Additionally, it defines the key terms used in this study and outlines all the research questions and objectives.

Chapter 3

Problem Definition

3.1 Introduction

The first chapter highlighted the importance of developing an intelligent platform or system to trade and manage carbon credits. The previous chapter reviewed the existing literature on trading and managing carbon credits. It is clear that the research in this area is in its initial phase, and only a few researchers are working in this area. In the previous chapter, we identified a number of shortcomings in the existing literature that need to be addressed in order to propose a complete methodology for carbon credits management and trading. This chapter formally defines and presents the problem we address in this thesis. section 3.2 highlights the research gaps defined in the literature review. section 3.3 provides a set of definitions of those terminologies that would be used while defining the research problems. We break the problem into four cohesive research issues and formally define each in section 3.4. We then outline the research objectives in section 3.5. Finally, section 3.6 concludes the chapter.

3.2 Research Gaps in the literature

Based on the systematic review of the existing body of literature, as described in detail in chapter 2, we identified the following gaps requiring further investigation:

1. To the best of our knowledge none of the existing literature develops an intelligent, trustworthy, and global platform for managing and trading carbon credits.

2. To the best of our knowledge none of the existing literature develops an intelligent mechanism to predict the future price of carbon credits based on multiple factors.

3. To the best of our knowledge none of the existing literature develops a mechanism to prevent the double counting problem in carbon credits at the project level before it occurs (from the source) or even within the project itself.

4. To the best of our knowledge none of the existing literature develops a marketplace mechanism based on blockchain that enables the stakeholders to trade carbon credits in a reliable manner.

3.3 Definition of Key Concepts

In this section, we present a formal definition of the terms and conceptst hath will be used to formally define the problem addressed in this thesis.

- **Carbon credits** Carbon credits are a permits that allow the company that holds it to emit a certain amount of carbon emission or other greenhouse gases, which can be traded if the total allowance is not used.(Kenton, 2019). One credit permits the emission of a mass equal to one ton of carbon dioxide. We use the above as our working definition of carbon credits.

- **Carbon trading**: Carbon trading is the trading of emissions of major greenhouse gases including carbon dioxide (CO2)(Perdan and Azapagic, 2011).

- **Double counting**: Double counting, initially a concept in economics, pertains to mistakenly tallying the value of a nation's goods and services multiple times (Fu et al., 2011).

- **Dynamic pricing**: Dynamic pricing is a business approach that sets the product price or service in a timely fashion to allocate the right service to the right customer at the right time (Lin, 2006).

- **Blockchain**: Blockchain technology is a distributed and decentralised database of all transactions or a public digital ledger of all records that have been executed and shared between participating parties. The consensus of most participants in the system verifies each transaction in the public ledger. Once entered, information in the blockchain can never be changed or erased (Crosby et al., 2016).

- **Artificial intelligence**: artificial intelligence is broadly defined as the ability of a computer or machine to perform tasks that typically require human intelligence (Hamet and Tremblay, 2017).

- **Machine learning**: machine learning is a subset of artificial intelligence that utilises algorithms and data applications to replicate the learning processes observed in individuals (Mahesh, 2020). In contemporary times, machine learning enables the accomplishment of intricate tasks by emulating human problem-solving methods.

- **Smart contract**: smart contract is primarily designed to digitally facilitate, validate, or enforce contract negotiation and performance (Giancaspro, 2017). Functioning as a computer protocol, smart contracts enable trustworthy transactions without the need for third-party involvement. They bring about heightened commercial efficiency, enhanced transparency, and transactional anonymity.

- **Ethereum.**: Ethereum functions as a peer-to-peer virtual machine network, provide a platform for developers to execute distributed applications (Dapps). Ethereum employs its decentralised blockchain to securely store and execute contracts through cryptographic methods(Jani, 2017). The distributed network of computers that Ethereum utilises ensures the reliability, security, and processing capacity necessary for the implementation of planned arrangements.

The next section provides the Research questions.

3.4 Research Questions

From the systematic literature review and in light of the shortcomings documented in Chapter 2 it is clear that there are several gaps in the existing literature on integrating blockchain and carbon credits. To address these gaps, the main research question in this thesis is as follows:

How can we develop an intelligent and tamper-proof platform for managing and trading carbon credits?

The main research question has been subdivided into the following sub-research questions:

- How to develop an intelligent, trustworthy, and global platform for managing and trading carbon credits.
- How can we develop an intelligent mechanism to counter the double counting of carbon credits?
- How can we intelligently and dynamically predict the price of carbon credits based on multiple factors?
- How can stakeholders reliably trade carbon credits through a secure and trustworthy marketplace?
- How can we validate the solutions developed for the above research questions?

3.5 Research Objectives

Based on the above research question and sub-questions, the research objectives of this thesis are as follows:

- **Objective 1:** To develop an intelligent global platform that reliably manages and trades carbon credits.

  To fulfil this objective, we will create the 'IBMCC' platform specifically designed for the intelligent management and trading of carbon credits. It is a decentralised structure built on a distributed peer-to-peer network system. Ethereum has been selected as the blockchain of choice due to its exceptional resilience and resistance to hacking, making it the most robust option available at present. The platform's architecture will leverage Ethereum's capabilities to ensure a secure and efficient environment for managing and trading carbon credits.

- **Objective 2:** To develop an intelligent mechanism to prevent the double counting of carbon credits.

  This objective will be addressed by developing an advanced mechanism that integrates machine learning and blockchain technology, targeting the prevention of double counting across and within individual projects, thereby offering a comprehensive solution to the challenge.

- **Objective 3:** To develop an intelligent approach to dynamically predict the price of carbon credits globally.

  We will achieve this objective by constructing an intelligent mechanism within the IBMCC platform that utilises machine learning technology to ensure a highly accurate rate of price prediction for carbon credits. Our *approach involves analysing various influencing factors to forecast the dynamic prices of carbon credits.*

- **Objective 4:** To develop mechanisms to enable the stakeholders to trade carbon credits in a reliable manner.

  To fulfill this aim, a marketplace will be developed to facilitate the trading of carbon credits. This platform will offer carbon credit holders the opportunity to buy or sell their credits. It will be structured to ensure public accessibility, decentralisation, and trustworthiness, thereby enhancing the transparency and integrity of carbon credit transactions.

- **Objective 5:** Build a prototype system to evaluate and validate the developed solution for the above objectives (1-4)

  To achieve this objective, the working of the developed platform will be evaluated using the Ethereum Ropsten network. This will be accomplished by testing its suitability for solving Research Questions 1 through 4 along specific standards.

Integrating blockchain technology into carbon markets offers practical solutions to key challenges. It prevents double counting by providing an immutable ledger, ensuring accurate carbon credit tracking. Advanced data analytics enable precise price predictions, helping stakeholders make informed decisions. Additionally, blockchain creates a secure, decentralized marketplace, enhancing trust and transparency in carbon credit trading.

Blockchain was chosen over other technologies for the provenance of carbon credits due to its unique ability to provide decentralized, tamper-proof records, ensuring transparency and trust in transactions. Unlike centralized databases, which can be vulnerable to manipulation or single points of failure, blockchain offers an immutable ledger that tracks every step in the lifecycle of a carbon credit. This reduces the risk of double counting and fraud, challenges that other technologies struggle to address as effectively. Furthermore, its smart contract capabilities allow for automated compliance with carbon market regulations, streamlining processes and enhancing operational efficiency.

3.6 Conclusion

In this chapter, the identified research gaps in the literature are outlined. Clear definitions for key terms relevant to this research are also provided. Additionally, the specific research questions that will be comprehensively addressed in this study are explored, followed by the research objective.

The next chapter will detail into the research methodology and present an overview of the potential solutions. This methodology will serve as a roadmap for how our objectives will be met.

Chapter 4

Research Methodology and Solution Overview

4.1 Introduction

In the previous chapter, the research gaps were identified and the research questions and research objective were detailed. This chapter presents an overview of the proposed solution and how the research questions will be solved. This chapter is organized as follows: Section 4.2 presents the new keywords used in this research. Section 4.3 outlines the selected research methodology used in the research. Section 4.4 presents an overview of the solution, highlighting research question 1 to research question 4. Section 4.5 concludes the chapter.

4.2 Key defenition

We define some definitions that are specific to this platform as follows:

- **IBMCC**: The Intelligent Blockchain approach for Managing Carbon Credits (IBMCC) refers to the proposed platform.
- **The stakeholder:** The term stakeholder represents the services requester and services provider to interact and trade with each other using the proposed marketplace.

4.3 Selected Research Methodology

This section, discusses the methodological approach used in this research to achieve the research objectives. The reason for choosing the design science research

(DSR) methodology is that it provides a structured framework for addressing complex problems through the development of innovative artifacts. By developing an initial prototype, the methodology allows for rigorous testing with different user groups, enabling the researcher to gather valuable feedback and assess whether the prototype meets the initially defined objectives. This iterative approach is fundamental in ensuring that the final product not only addresses the identified issues but also evolves based on user needs and contextual requirements.

Moreover, design science research emphasizes the importance of relevance and utility. By focusing on creating a working artifact that serves as a proof-of-concept, the methodology ensures that the outcome is not merely theoretical but has practical implications and can be applied in real-world settings. This aspect is particularly important when the working artifact is intended to be made accessible as a service, as it increases the likelihood of user adoption and satisfaction.

Another justification for employing DSR is its dual focus on both rigor and relevance. This approach fosters collaboration between researchers and practitioners, ensuring that the developed solutions are grounded in both academic theory and practical application. This alignment enhances the credibility of the research and facilitates knowledge transfer, ultimately leading to a greater impact on the field.

Furthermore, DSR encourages continuous improvement and innovation through its iterative cycles of design, evaluation, and refinement. In cases where initial objectives are not met, the researcher is prompted to revisit the design process, explore alternative solutions, and adapt the artifact accordingly. This flexibility not only supports the refinement of the product but also cultivates a culture of learning and adaptation, which is essential in today's rapidly evolving technological landscape.

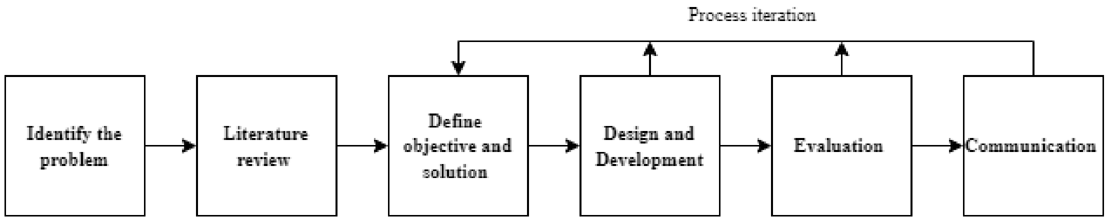

Figure 4.1 : Design science research methodology (Peffers et al., 2007)

4.3.1 The design science research methods:

The design science research methodology follows a systematic, phased approach to problem-solving. As shown in Figure 4.1 , this method guides the development of a solution through clearly defined steps. Each phase builds on the previous one, from identifying the problem and reviewing literature, to defining research objectives, designing and testing a solution, with ongoing iterations to refine and improve the final outcome.These phases are detailed as follows:

- Phase 1: Identify the problem:During this initial phase, we identify the gaps in the existing literature related to the management of carbon credits through blockchain technology.

- Phase 2: Literature Review: In this phase, we conduct a comprehensive literature review to identify the gaps in the existing body of work related to the management of carbon credits. This process is extensively documented in Chapter 2 of this thesis.

- Phase 3: Defining Research Objectives and Solution: We derived the research objectives based on the identified gaps and research questions during this phase. Chapter 3 provides an in-depth exploration of this phase. Additionally, Chapter 4 outlines the overview solution strategy devised to address the research questions.

- Phase 4: Design and Development In this pivotal phase, we detailed the building of a prototype utilising a combination of artificial intelligence techniques and blockchain as a proof-of-concept. Chapters 5, 6, and 7 of this thesis elaborate on the development of solutions for research questions 2,3 and 4, respectively.

- Phase 5: Evaluation and Testing: We evaluate the effectiveness of the constructed models by employing various metrics to address research question 5. Each of chapter 5,6 and 7 have an evaluation section.

- Phase 6: Communication: Upon obtaining outcomes, we prepare for publication in prestigious conferences and international peer-reviewed journals, with a focus on maximising the dissemination of our research findings.

  Iterative Process: The design and development phase, along with the evaluation phase, undergo iterative cycles throughout the research work. This iterative approach enables a deductive cognitive process, facilitating the enhancement of the solution as new insights about the artifact and its environment emerge during both development and evaluation. This iterative process entails revisiting the objective definition phase from partial research completion, ensuring continuous improvement and adaptability in response to evolving insights.

4.4 Solution Overview

This section discusses the overview of the (IBMCC) platform, which is built to manage and trade carbon credits.

4.4.1 Architecture of the IBMCC platform.

(RQ1)

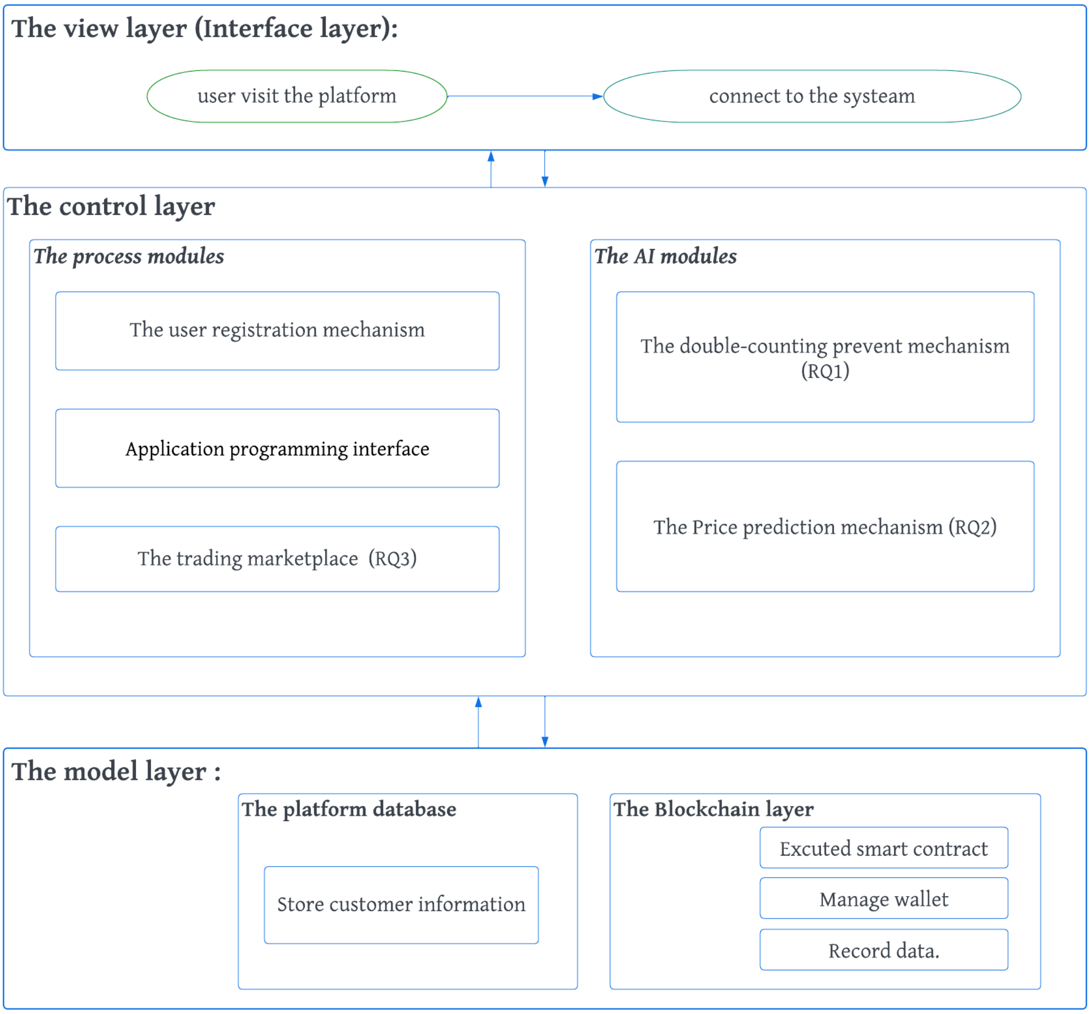

Figure 4.2 : The IBMCC platform

The blockchain-based carbon credits management platform is divided into three main layers, as shown in Figure 4.2.

Layer 1: This is the view layer, an interface layer that functions as a bridge connecting various modules or subsystems within the platform. Serving as a communication interface, it enables seamless interaction between these elements and facilitates user interaction with the platform.

Layer 2: This is the control layer, tasked with supervising and directing the overall operations of the platform. It acts as the central authority that orchestrates and governs interactions among various modules. Within this layer, two primary modules exist: the AI modules and the process modules. The AI modules encompass two models—namely, the double counting prevent model and the price prediction model, On the other hand, the process modules comprise three components: the user registration model, the API model, and the marketplace model.

Layer 3, known as the model layer, plays a pivotal role in the platform's architecture. This layer incorporates two distinctive types of databases, each serving specific functions. Firstly, the platform database serves as a comprehensive repository for storing and managing all customer information, ensuring a centralized and organized storage system. Secondly, the blockchain database operates as the backbone for executing smart contracts and meticulously recording all pertinent information related to transactions and interactions within the platform. Together, these databases in Layer 3 form a robust foundation, facilitating efficient data management and transactional processes.

The key components of the (IBMCC) platform are the Double Counting Sentry for accurate accounting, Carbon Credits Market Predictive Dynamics for market forecasts, and the Green Hub for eco-trading.

Section 4.4.2 to Section 4.4.4 presents an overview of the solution of each of the objectives in this thesis.

4.4.2 Overview of the solution for RQ2

The double-counting sentry is presented as a solution to Research Question 2. This mechanism is built using the Ethereum blockchain which prevents the double counting issue from occurring on two levels, across multiple projects and within a single project. To prevent double counting from happening across projects, through this mechanism; every project registered in any registry will be stored in the blockchain ledger as a set of metadata. Whenever a new registry occurs in any of the registry lists, the mechanism will check the entered data and determine if the project exists and is already registered in the data for another registry. If so, the system will fail the new registry for the project. This will solve the problem from the source before it even occurs, effectively solving the double-counting problem across the different projects. Moreover, as an additional solution to address the issue of double counting within a project, we propose the Carbon Credits Unique Identifier (CCUI) mechanism within the double counting sentry. This mechanism automatically assigns an ID number to each credit issued for a project, helping to prevent the carbon credit from being counted more than once.

4.4.3 Overview of solution for RQ3

To address Research Question 3, we implemented an intelligent mechanism in our platform. This mechanism, called carbon credit market predictive Dynamics, autonomously takes into account the various dynamic factors to predict carbon credit prices. These factors encompass real-time data that are subject to constant change. The predictive model encompasses a wide array of variables. It considers current prices, levels of CO2 emissions, evolving regulatory frameworks, and the specific country context. This multifaceted analysis allows us to provide more precise and adaptable forecasts for global carbon credit prices. As a result, stakeholders are empowered to make well-informed decisions in a swiftly evolving market landscape.

4.4.4 Overview of solution for RQ4

To address Research Question 4, we created the green hub, which is a marketplace for carbon credits trading. The marketplace will be developed to facilitate the trading of carbon credits. This platform will allow carbon credit users to buy or sell their credits. It will be structured to ensure public accessibility, decentralisation, and trustworthiness, thereby enhancing the transparency and integrity of carbon credit transactions. The marketplace is blockchain-based.

4.4.5 Overview of solution for RQ5

To address Research Question 5, the IBMCC platform developed in this research was assessed using the Ethereum Ropsten network. This evaluation primarily involved testing its effectiveness in tackling Research Questions 1 through 4.

The IBMCC platform operates through a straightforward process as follow:

- Step 1: The platform will be built using the Ethereum blockchain.
- Step 2: The chosen algorithms will be implemented into the models in the artificial Intelligence layer.
- Step 3: The users have to register on the platform so that they can use it. 3a) if the user is new, a new registration is needed. 3b) if the user is a returning user, then the login is needed.
- Step 4: After registration, each user will have a private wallet that is created by the system.
- Step 5: The user will be directed to the marketplace.
- Step6: Several actions are undertaken in the marketplace:
- Step 7: The price of the carbon credits will be set based on a number of factors.
- Step 8: The double counting model will activated and updated with every registration.
- Step 9: The smart contract is executed to transfer the ownership between the buyer and the seller.
- Step10: The transaction will be approved by the miners and added to the blockchain.

4.4.6 Testing and Verification of the Solution

- **The validation of objective 1:** This particular objective focuses solely on the implementation aspect. It serves as the foundational step where we develop the solution, which is crucial for validating the subsequent objectives (2-3-4). To achieve this, we will employ a diverse array of technologies, each selected for its specific contribution to the system's overall functionality. Within the scope of this objective, our primary task is the practical realisation of the IBMCC solution. This involves technical development and ensuring that each component integrates seamlessly to form a cohesive and efficient system. This phase is critical as it lays the groundwork on which the other objectives will be assessed and validated.

- **The validation of objective 2:** To evaluate the system's ability to detect the double counting of credits within a single project, we conduct a comprehensive analytical comparison through two separate iterations. In the first iteration, we execute the experiment with the proposed algorithm operating normally. We process and analyze all carbon credits using this scenario as the baseline to assess the algorithm's performance under standard conditions. In the second scenario, we conduct the experiment by intentionally introducing manipulated or duplicated carbon credits into the system to assess the algorithm's ability to differentiate between genuine and manipulated credits.

  To further ascertain the system's capability in identifying the double counting of carbon credits across multiple projects, we employ a structured approach. Initially, we utilize a dataset from the registry to simulate project submissions that could potentially reflect double registration attempts within multiple carbon credit registries. Subsequently, each registration attempt is meticulously logged on a global blockchain ledger, uniquely marked with project identifiers along with comprehensive metadata. The next phase involves the deployment of smart contracts within the blockchain framework to automatically scrutinize new registrations against extant records, bringing any potential duplicates to light. Upon detection of duplicates, a cooperative consensus mechanism among the registries is activated to authenticate whether the registration is exclusive or replicated. Depending on the outcome, the system updates the registry status: for unique projects, registration proceeds successfully, whereas for duplicates, the registration process is halted.

- **The validation of objective 3:** To evaluate the model's accuracy and robustness using the selected dataset, we undertake a structured methodology encompassing several key phases. Initially, we load and preview the dataset to understand its structure and content. The subsequent stage, data preprocessing, involves preparing the data for modelling; this includes addressing missing values, encoding categorical variables, and partitioning the dataset into distinct training and testing sets. Following this, we move to model training, where we will train the selected predictive models using the training set. The next step, performance evaluation, entails using the testing set to calculate key performance indicators such as mean absolute error (MAE), mean squared error (MSE), and the R^2 score. Finally, we will compare these metrics against established benchmarks to gauge the model's effectiveness.

- **The validation of objective 4:** Our project involves the development and implementation of a marketplace, which acts as a dedicated platform for facilitating the trade of carbon credits among users. This marketplace is envisioned to be a dynamic and user-friendly environment, where participants can engage in the buying and selling of carbon credits with ease and security. By implementing this marketplace, we aim to create a centralized hub for carbon credit trading that is not only efficient and reliable but also contributes to the broader goal of environmental sustainability by facilitating the trade of carbon credits in a transparent and accessible manner.

4.5 Conclusion

In this chapter, a comprehensive analysis of the methodological approach utilized to bridge the gaps highlighted in the literature review has been conducted. The design science research methodology was meticulously chosen as the most suitable framework for this study, given its emphasis on the creation and evaluation of artifacts designed to solve identified problems.

Additionally, the chapter delved into the intricate process involved in developing the IBMCC platform. This innovative platform stands at the intersection of blockchain technology and carbon credits management, representing a significant leap forward in this field. The integration of blockchain technology promises enhanced security, transparency, and efficiency in the management of carbon credits, marking a pivotal advancement in environmental sustainability efforts. Furthermore, this chapter provided a detailed overview of the proposed solutions for each objective outlined in this research. These solutions were tailored to meet the specific objectives and designed to contribute to the broader aim of the study collectively.

Looking ahead, the subsequent chapter meticulously outlines the second research objective of this thesis, which concerns the development of a double-counting prevention mechanism. We investigate the methodological steps involved in crafting this solution, elaborating on its significance and implications.

Chapter 5

The Double Count Sentry

5.1 Introduction

In the previous chapter, we overviewed our proposed platform, the Intelligent Blockchain for Managing Carbon Credits (IBMCC).

In this chapter, we elaborate on the strategies to mitigate the double counting issue, presenting a two-tiered framework designed to address this challenge comprehensively. This model operates at both the project level and across different project registries, offering a holistic solution aligned with research objective two. Additionally, we showcase the outcomes of validating and implementing our proposed solution to research question two. To solve this very complicated and unsolved issue in the carbon market, we proposed a novel approach involving two layers of checks and balances (the double counting sentry) to solve the double counting problem at both the project level (ensuring that project developers do not receive credits from multiple certification bodies for the same emission reduction project) and within the projects itself. (no credits for the same project counted twice).Our two-layered solution is shown in Figure 5.1

To address this issue at the individual project level, we propose assigning a unique identifier to each carbon credit and storing this data on the blockchain. This approach enhances transparency and traceability within the carbon credit system, thereby facilitating more effective management and oversight. More details of this approach are provided in section 5.2. Additionally, at the project level, one potential approach to this problem involves the establishment of a global carbon blockchain.

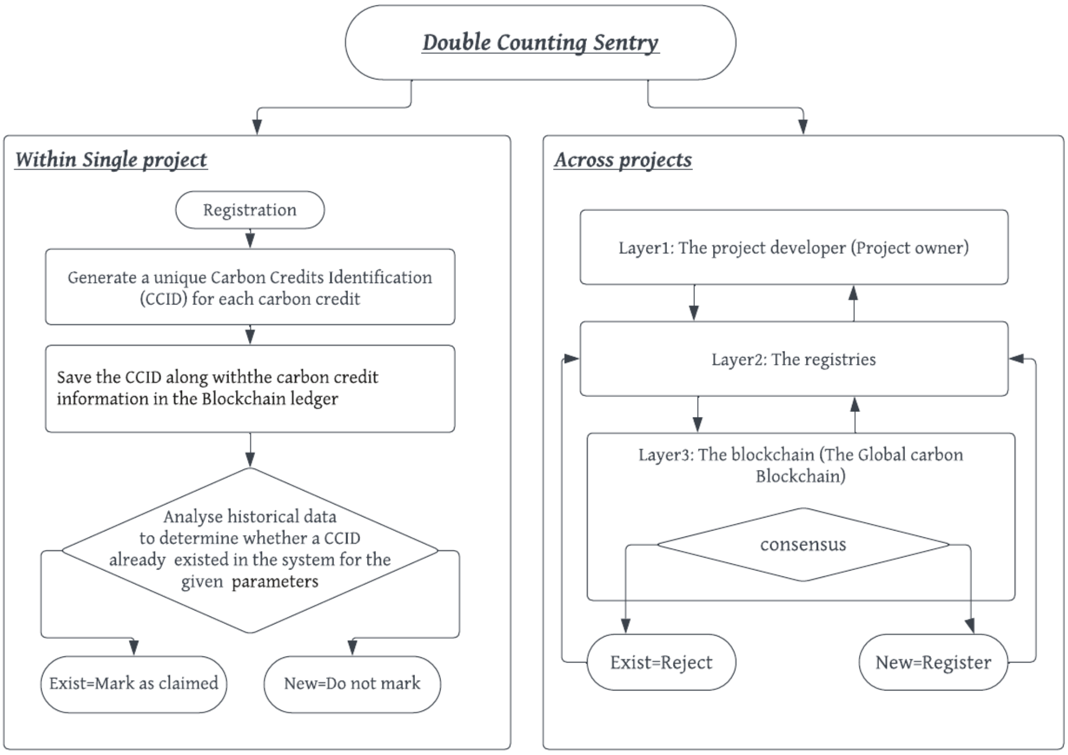

Figure 5.1 : The Double Counting Sentry Overview.

In this system, all registries are consolidated and data are shared in a decentralised manner using blockchain technology. When a new project attempts to register with any registry, the system would thoroughly check various attributes to verify that the project has not previously been registered with another registry. Section 5.3 will discusses this approach in detail. To validate our approach, we develop a blockchain-based system and leveraged various technologies for testing purposes. These technologies include:

1. Blockchain: as defined in Chapter 4, blockchan is utilized for storing and accessing registry data and serves as a decentralised and distributed digital ledger, ensuring the immutability of records.

2. Python programming language: Python is a simple and elegant syntax and yet is a powerful and general-purpose programming language (Sanner, 1999), we employed to develop the necessary codebase for our system.

3. MetaMask: Acting as a bridge between Ethereum and standard web browsers, MetaMask facilitates Ethereum transactions. In our project, we integrated the MetaMask plugin with Chrome to connect with blockchain technology.

The chapter is structures as follows: section 5.2 details the methodology of the proposed solution to prevent double counting within a single project. section 5.2, discusses the proposed solution to the problem across different registries, the implementation of our proposed solution, the selected dataset, and insights into the validation process, as well as the analysis and discussion of the results obtained from the evaluation, are presented in section 5.4. Finally, Section 5 concludes the chapter.

5.2 Solving the double counting problem within a single project

This section explains the logic of double counting sentry within a single project.

5.2.1 The system workflow

The workflow of this approach are as follows:

- Step 1: Register the carbon credits to the system through the registration system which is explained in detail in Chapter 7.
- Step 2: Utilize blockchain technology to create a secure, immutable ledger.
- Step 3: Implement the advanced AI module: we create the carbon credits ID assignment and duplicate detection algorithm, especially for this system.
- Step 4: Use the carbon credits ID assignment and duplicate detection algorithm to scrutinise each carbon credit identification (CCID) in the blockchain ledger.
- Step 5: Generate a unique CCID for each carbon credit using smart contracts, ensuring each credit is distinct and traceable.
- Step6: Analyse historical data to determine whether a CCID has already been counted or utilised in the system, effectively preventing double counting.
- 6.1 If the AI module identifies a CCID as previously counted, automatically mark this credit as 'COUNTED' in the ledger.
- 6.2 For new or uncounted CCIDs, maintain their status as unmarked, indicating availability for use or trading.
- Step 7: Keep a transparent and accessible record of all transactions, updates, and statuses of carbon credits, enhancing trust and credibility in the system.

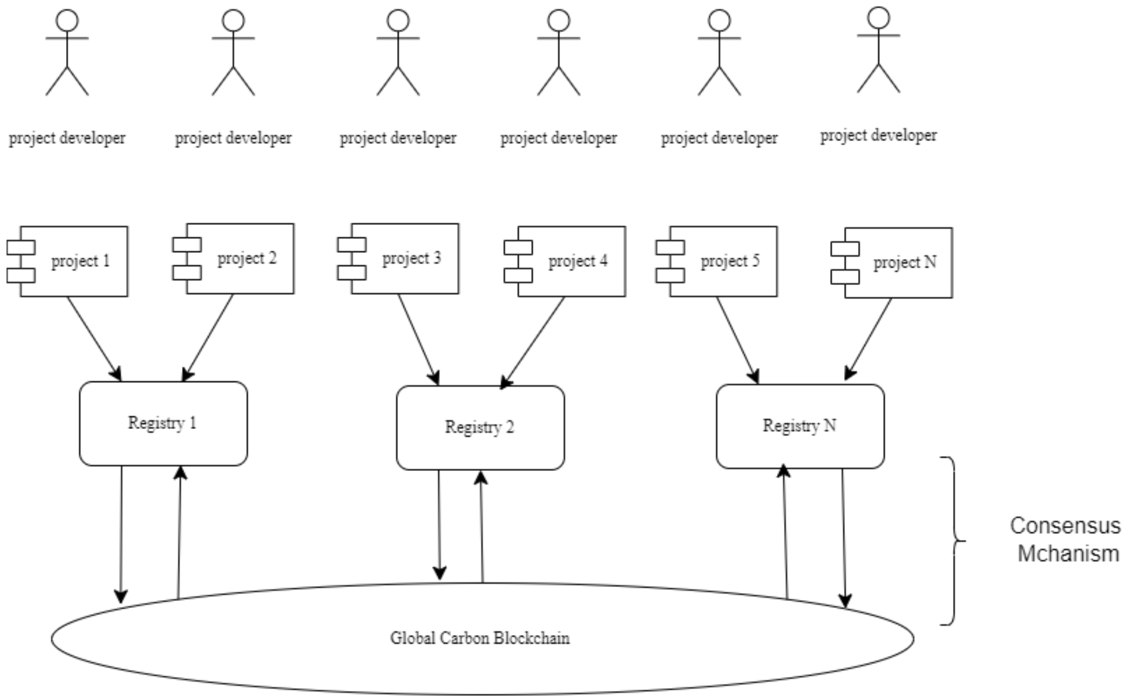

Figure 5.2 : The proposed solution architecture.

5.3 Solving the problem across registries

This section explains the logic of the double counting sentry across all the registries.

The main purpose of proposing this solution is to avoid multiple registries of carbon credit projects in different registries. Carbon offsets/project owners apply to more than one registry and issue a number of carbon credits for the same project. Currently, each registry works individually, and there is no mechanism to combine all the registries' data, which results in a global issue when the emission reduction is not accurate. To prevent the issue of double-counting in carbon credit management, we use a global carbon blockchain to maintain a single version of the truth across multiple registries as shown in Figure 5.2. This blockchain serves as a universal ledger listing all the registered projects and their details. Before any project is officially registered in any local registry, the registries (acting as miners in this blockchain network) have to reach consensus to validate the project's uniqueness and legitimacy. In doing so, the problem of double counting is solved before it even occurs.

5.3.1 Algorithm for addressing the double counting problem across multiple registries

Algorithm 1 present the Algorithm used for addressing the double counting problem across multiple registries

5.3.2 The workflow to address the double counting problem across multiple registries

The workflow of this approach is as follows:

1. Initialization:

   o Initialize an empty global carbon blockchain.

   o Initialize a list of registries that are allowed to write to the blockchain.

2. Project Registration Request:

   o When a project developer submits a project to a local registry, that registry prepares a new block containing all the project details such as project ID, project name and activities involved.

3. Consensus Request:

   o The local registry sends a consensus request to the global carbon blockchain network. All registries (miners) are notified to validate this new project.

4. Validation:

   o Each registry checks its local database and the pending block to validate the project's uniqueness.

Algorithm 1 Algorithm for addressing the double counting problem across multiple registries

Initialization:

Global Carbon Blockchain ← empty list

Allowed Registries ← empty list

function SUBMITPROJECTTOREGISTRY(projectDetails)

newBlock ← CreateBlock(projectDetails)

LocalRegistry.PrepareBlock(newBlock)

function SENDCONSENSUSREQUEST(newBlock) **for** *each registry in Allowed Registries* **do**

end

Registry.ValidateBlock(newBlock)

function VALIDATEBLOCK(newBlock) **if** *IsBlockUnique(newBlock)* **then**

end

SendValidVote() **else**

end

SendInvalidVote()

function PROCESSCONSENSUSVOTES(votes) **if** *ValidCount / Length(votes) > 0.51* **then**

end

AddBlockToGlobalBlockchain(newBlock) **else**

end

RejectBlock()

function UPDATELOCALREGISTRIES(newBlock) **for** *each registry in Allowed Registries* **do**

end

Registry.UpdateLocalDatabase(newBlock)

o If valid, the registry sends a valid vote. Otherwise, it sends an invalid vote.

5. Consensus Decision:

   o If more than 51% of the registries send a valid vote, the block is added to the global blockchain. Otherwise, the block is rejected, and the project cannot be registered.

6. Update Local Registries:

   o After consensus is reached, all local registries update their local databases to include the newly registered project if it is validated.

5.4 The system Evaluation

5.4.1 Testing the performance of the double counting sentry within a single project

The selected dataset is used to evaluate the system

To test and verify the performance of our proposed solution to solve the double counting problem within single projects, we generated data samples from the system input and used them as a dataset for testing purposes. A snapshot of the carbon credits samples is shown in Figure 5.3.

the evaluation process

To evaluate the system, we follow the following steps:

1. Execute the experiment with the proposed algorithm operating normally.

2. Process and analyse all carbon credits using the algorithm without external interference.

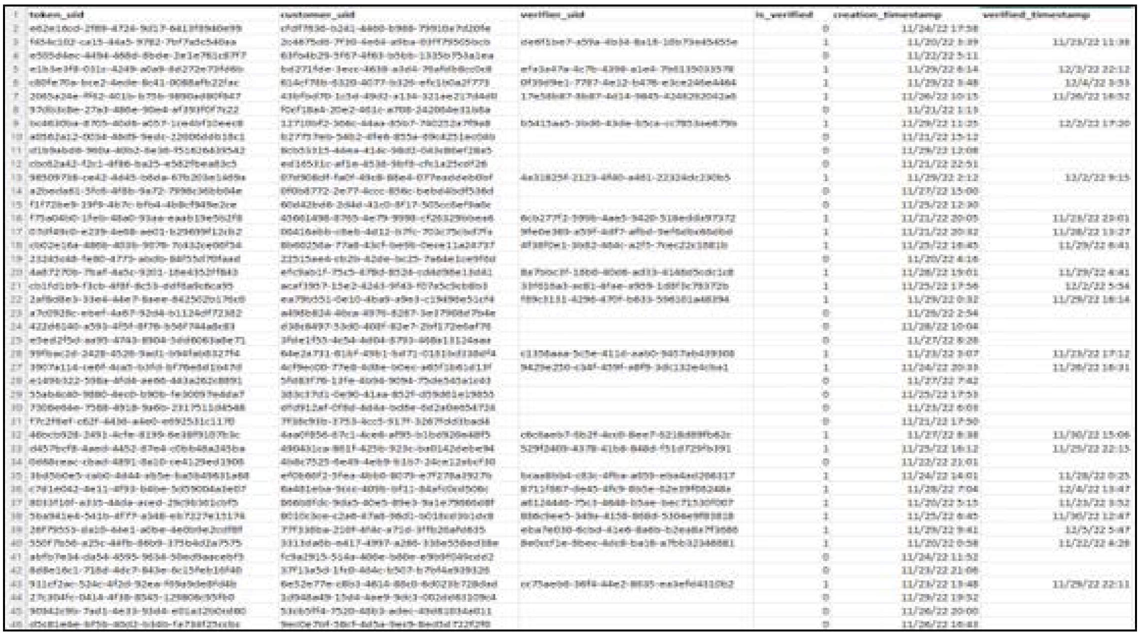

Figure 5.3 : Carbon credits samples

3. Accurately identify that no carbon credits have been counted previously and that they are all unique.

4. Use this scenario as the baseline for assessing the algorithm's performance under standard conditions.

5. Conduct the experiment by intentionally modifying some carbon credits.

6. Introduce manipulated or fake carbon credits into the system.

7. Assess the algorithm's ability to detect and differentiate between genuine and manipulated credits.

Result and Discussion.

This section elaborates the experiment conducted to test our proposed system. In addition to detailing the process followed, we also outline the evaluation procedures employed to ascertain the effectiveness of our system. To test the efficacy of the proposed algorithm, we conduct experiments under two scenarios: one with the algorithm operating as intended and another with the deliberate manipulation of some credits.

- ***Part 1: Verification of Unique Carbon Credits***

The first part of the experiment aimed to validate the uniqueness of the carbon credits generated on the local Ethereum blockchain network. This is to ensure that each carbon credit could be distinctly identified without any duplication.

1. During this phase, 500 carbon credits were created, each with a universally unique identifier (UUID) version 4 as the unique token identifier (token_UID).
2. The carbon credit counter program was then deployed to verify these identifiers against the blockchain records.

- ***Results***

The counter program successfully confirmed the uniqueness of all 500 carbon credits, with no duplicates detected. This result was consistent with the experiment's expectations and verified that the UUID version 4 mechanism effectively provided unique identifiers for each carbon credit.

From the above execution log of the carbon credit counting program, as shown in Figure 5.4 the program identified 500 unique carbon credits on the local Ethereum blockchain network, which matches the experiment records. No duplicated carbon credits were identified This proves that our system is a well-implemented solution for the problem of double counting within a single project. The findings from this part of the experiment underscore the effectiveness of using UUID version 4 identifiers within a blockchain context. This supports the integrity and reliability of blockchain

```
[*] Starting the carbon credit counting progress...
[*] Trying to connected to the local Ethereum Blockchain network...
[*] Successfully connected to the local Ethereum Blockchain network!
Detected carbon credit #1:
        token unique identifier: 28217be9-60fb-4a84-843b-825568073c10,
        owner identifier: 5a36aa1b-c83c-4918-bef6-d542a893804c
Detected carbon credit #2:
        token unique identifier: da5c6d78-8148-438c-b532-ac5003dacf72,
        owner identifier: b5c8b5e6-0dcf-45af-adb2-de1cd974aff0
Detected carbon credit #3:
        token unique identifier: c9c02f87-f235-45cc-bc89-7fd5e4fb0a7e,
        owner identifier: 56f2e223-e5b8-41a2-8650-0ccfd2fbca3f
Detected carbon credit #4:
        token unique identifier: f7959f9e-1e4f-450b-8bcf-2f331f5f1f01,
        owner identifier: 94e614c1-45d5-4334-9de5-011d9933b2e0
Detected carbon credit #5:
        token unique identifier: 9c97373b-b12c-440f-9742-00ad36d0cbb7,
        owner identifier: 494f8670-15aa-4368-a888-554eb5bc8d5d
Detected carbon credit #6:
        token unique identifier: bed72f14-cf23-4529-b6bc-01e05e6654c1,
        owner identifier: 2b3e16ae-7424-47f0-8e2f-84a38ae6a206
Detected carbon credit #7:
        token unique identifier: a7091d30-50ef-4530-916f-b853b537d72c,
        owner identifier: 38821638-e7c8-4077-b1a5-a011a72fe872
Detected carbon credit #8:
...
[*] Carbon credits verification has completed.
[*] Total number of carbon credits identified: 500

[*] No duplicated carbon credits identified.
```

Figure 5.4 : Screenshot of the double counting algorithm outcome

technology for carbon credit issuance, critical for maintaining trust and preventing fraud in environmental credit markets.

- ***Part 2: Detection of Duplicate Carbon Credits.***

1. The second part of the experiment focused on testing the carbon credit counter program's ability to detect and report duplicated carbon credits. This was to challenge the system's capability to identify breaches of uniqueness rules.

2. For this test, from the 500 credits used in this experiment,50 carbon credits were intentionally duplicated within the database to simulate the potential issue of double counting.

3. The carbon credit counter program was then tasked with identifying these duplicates among the existing entries.

- **Results**

An additional experiment to cover the duplicated carbon credits (duplicated token_UUID) in the database was conducted to evaluate whether or not the designed carbon credit counting program with the intelligent approach is valid.

Figure 5.5 shows that the carbon credit counter can identify duplicated carbon credit tokens. Duplicated tokens either do not have a unique identifier or they have the same ID number, violating our designated rules. The program's intelligent approach successfully identified the duplicates, flagging them as violations of the system's rules for unique token identifiers. The system reported 450 unique carbon credits and identified 50 duplicates. As shown in Figure 5.5 the success in detecting duplicate carbon credits demonstrates the robustness of the counter program's validation process. It highlights the system's potential utility in real-world applications where the prevention of double counting is paramount. The experiment also indicates the need for such intelligent systems to safeguard the integrity of carbon credit markets. This two-part experiment collectively shows that the system can both assign unique identifiers to carbon credits and effectively detect and manage duplicates, addressing a significant challenge in the carbon trading sector.

5.4.2 Testing the performance of the double counting sentry across registries

The selected dataset was used to evaluate the system

To test this model, the following datasets are used: Voluntary-Registry-Offsets-Database–v8-May-2023.xlsx, which is a publicly available and can be accessed through this link ….. Only Four data types are used from the dataset to get the best result, namely project ID, project NAME, project TYPE and NUMBER of credits issued as shown in Figure 5.6. The reason for choosing this public dataset is that it provides comprehensive insights into voluntary carbon offset projects.

```
Detected duplicated carbon credit token: 7c75610a-6bc3-4579-97b9-1402c7c28161
Detected duplicated carbon credit token: f8f3182d-9dfb-47a1-bc7d-9f5269a1b497
Detected duplicated carbon credit token: c495b286-404a-40da-aa1a-859074ebb634
Detected duplicated carbon credit token: 06db4f3f-1175-468f-a972-a19ea4ea9678
Detected duplicated carbon credit token: 31ae7a70-f98a-4b8f-b8f3-24bc9c96f829
Detected duplicated carbon credit token: b0e992a3-5f4d-4aed-90e8-e3c49e93f7cc
Detected duplicated carbon credit token: a7b5817c-c8f6-401d-8a45-cdfdf76b2f4f
Detected duplicated carbon credit token: ddeaa055-254d-4f88-b8fb-7c81f46d4f2e
Detected duplicated carbon credit token: 339609b1-f8ef-409d-b564-e1aa7ab072e4
Detected duplicated carbon credit token: 0afe9a47-06d2-4edf-ac6c-c7ebb2d8a2b6
Detected duplicated carbon credit token: fd8c141e-22b2-4c69-b4bc-17e04751c9a8
Detected duplicated carbon credit token: 86c475e2-742b-40fc-bb66-48517e4cadf9
Detected duplicated carbon credit token: 3de3423a-2862-4532-882d-73957594c159
Detected duplicated carbon credit token: e15a21bb-5c30-4d36-9198-7d5d096ddea6
Detected duplicated carbon credit token: dc2c4ee4-6477-4465-8f5c-a3af0d93faf1

[*] Carbon credits verification has completed.
[*] Total number of carbon credits identified: 450
[*] Total number of duplicated carbon credits identified: 50
```

Figure 5.5 : Screenshot of the double counting outcome part 2

Voluntary Registry Offsets Database			
All 7933 offset projects are visible			1,806,128,232
Filter & sort projects with drop down arrows. Use Data menu to clear filters.			
Project ID	**Project Name**	**Type**	**Total Credits Issued**
ACR102	Air Bag Gas Substitution	SF6 Replacement	7,984,006
ACR103	Inland Empire Anaerobic Ag Digester	Manure Methane Digester	44,202
ACR104	Ankotrofotsy Community-based Reforestation and Carbon Offset	Afforestation/Reforestation	0
ACR105	Boa Vista A/R	Afforestation/Reforestation	2,572,210
ACR106	Brickyard LFG to Energy	Landfill Methane	138,492
ACR107	Camargo Fuel Substitution	Fuel Switching	1,138
ACR108	San Juan National Forest Carbon Demonstration Project	Afforestation/Reforestation	0
ACR109	Chesapeake Mizer Pneumatic Retrofit	Pneumatic Retrofit	541,804
ACR110	Chicago LFG to Energy	Landfill Methane	62,262
ACR111	Devon Mizer Pneumatic Retrofit	Pneumatic Retrofit	5,724
ACR112	Dolton LFG to Energy	Landfill Methane	159,336
ACR113	Greater New Bedford LFG	Landfill Methane	713,162
ACR114	GreenTrees ACRE (Advanced Carbon Restored Ecosystem)	Afforestation/Reforestation	6,268,282
ACR115	Lower Mississippi Valley Reforestation	Afforestation/Reforestation	13,422
ACR116	Societe VERAMA Madagascar Afforestation Project	Afforestation/Reforestation	0
ACR117	Merit Energy Geo-Seq	Carbon Capture & Enhanced Oil Recovery	7,308,664
ACR118	Monell Geo-Seq	Carbon Capture & Enhanced Oil Recovery	1,748,409
ACR119	North Country LFG	Landfill Methane	1,592,397
ACR120	Petrosource Geo-Seq	Carbon Capture & Enhanced Oil Recovery	2,181,419

Figure 5.6 : Sample of the used dataset

Evaluation steps

The following steps are used to evaluate the performance of the proposed solution.

- Step 1: Utilize the registry data dataset to create simulated project submissions that mirror potential double registration attempts across multiple carbon credit registries.
- Step 2: Log each registration attempt on a global blockchain ledger with unique project identifiers and detailed project metadata.
- Step 3: Use smart contracts on the blockchain to automatically compare new registrations against existing records and flag potential duplicates.
- Step 4: When duplicates are detected, trigger a consensus mechanism among registries to verify if the project registration is unique or a duplicate.
- Step 5: The registry states
- If the project is unique, the project will be registered successfully.
- If the project is duplicated, the project registry will fail.

Results and discussion

To measure the performance of the proposed method, the platform was tested using the previously mentioned dataset, and it successfully detected the duplicated registry of projects for all test tries, as shown in Figure 5.7. If there are two or more duplicated attributes, they will not pass the validation process. Detecting double counting in carbon credit platforms is critical to prevent inaccuracies and maintain the credibility of the data. To identify potential duplicates, the platform employs a stringent validation process that examines four key attributes, namely Project

E1 validate_status

	project_i	project_name	project_type	total_credits_issued	validate_status
205	GS10904	Up Energy Improved Cookstoves Programme, Uganda - CPA No 006	Wind	77262	Failed
206	GS10905	Up Energy Improved Cookstoves Programme, Uganda - CPA No 007	Wind	77262	Failed
207	GS10906	Up Energy Improved Cookstoves Programme, Uganda - CPA No 008	Wind	77262	Failed
208	GS10907	Up Energy Improved Cookstoves Programme, Uganda - CPA No 009	Wind	77262	Failed
210	GS10909	Up Energy Improved Cookstoves Programme, Uganda - CPA No 011	Energy Efficiency - Domestic	77262	Failed
212	GS10910	Up Energy Improved Cookstoves Programme, Uganda - CPA No 012	Energy Efficiency - Domestic	77262	Failed
264	GS11218	GS10818 - Dissemination of Improved Cookstoves in India by Greenway - Dissemination of Improved C	Energy Efficiency - Domestic	56115	Failed
444	GS1697	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	80810	Failed
445	GS1698	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	80809	Failed
446	GS1699	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	80809	Failed
447	GS1700	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	80810	Failed
452	GS1705	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78442	Failed
453	GS1706	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
454	GS1707	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
455	GS1708	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78442	Failed
456	GS1709	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
457	GS1710	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78442	Failed
458	GS1711	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
460	GS1713	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
461	GS1714	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78442	Failed
462	GS1715	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
463	GS1716	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
464	GS1717	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78442	Failed
465	GS1718	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78441	Failed
471	GS1724	GS1239 Sichuan Rural Poor-Household Biogas Development Programme PoA- CPA Nb. SCHHBG-2012-	Energy Efficiency - Domestic	78678	Failed

Figure 5.7 : Screenshot of the failed projects when two attributes match

ID, Project Name, Project Type, and Total Credits Issued. By comparing these attributes, the platform aims to flag instances where projects may be erroneously counted multiple times.

Furthermore, the platform's strict criterion stipulates that any two or more duplicated attributes result in the project's rejection. This ensures that even minor attribute discrepancies can trigger a flag for potential double counting. By adhering to this rigorous validation process, the platform mitigates the risk of double counting and maintains the accuracy and integrity of the data.

Overall, the focus on detecting double counting underscores the platform's commitment to transparency and reliability in managing carbon offset projects. By implementing a robust validation mechanism that considers multiple attributes, the platform safeguards against inaccuracies and ensures that carbon credits are accurately accounted for, thereby fostering trust among stakeholders and facilitating effective carbon offset management.

As shown in Figure 5.7, the system fails to register projects when two attributes

project_i	project_name	project_type	total_credits_issued	validate_status
ACR102	Air Bag Gas Substitution	Industrial Gas Substitution	7984006	Passed
ACR103	Inland Empire Anaerobic Ag Digester	Livestock Waste Management	44202	Passed
ACR105	Boa Vista A/R	Forest Carbon	2572210	Passed
ACR106	Brickyard LFG to Energy	Landfill Gas Capture & Combustion	138492	Passed
ACR107	Camargo Fuel Substitution	Fuel Switching	1138	Passed
ACR109	Chesapeake Mizer Pneumatic Retrofit	Industrial Process Emissions	541804	Passed
ACR110	Chicago LFG to Energy	Landfill Gas Capture & Combustion	62262	Passed
ACR111	Devon Mizer Pneumatic Retrofit	Industrial Process Emissions	5724	Passed
ACR112	Dolton LFG to Energy	Landfill Gas Capture & Combustion	159336	Passed
ACR113	Greater New Bedford LFG	Landfill Gas Capture & Combustion	713162	Passed
ACR114	GreenTrees ACRE (Advanced Carbon Restored Ecosystem)	Forest Carbon	6268282	Passed
ACR115	Lower Mississippi Valley Reforestation	Forest Carbon	13422	Passed
ACR117	Merit Energy Geo-Seq	Carbon Capture & Storage (CCS)	7308664	Passed
ACR118	Monell Geo-Seq	Carbon Capture & Storage (CCS)	1748409	Passed
ACR119	North Country LFG	Landfill Gas Capture & Combustion	1592397	Passed
ACR120	Petrosource Geo-Seq	Carbon Capture & Storage (CCS)	2181419	Passed
ACR121	Pike's Peak Geo-Seq	Carbon Capture & Storage (CCS)	2866515	Passed
ACR122	Romeoville LFG to Energy	Landfill Gas Capture & Combustion	52496	Passed
ACR123	Salt Creek Geo-Seq	Carbon Capture & Storage (CCS)	7675073	Passed
ACR124	Schneider Anti-Idling	Transport / Fleet Efficiency	42916	Passed
ACR125	SEESA Solar Electrification	Renewable Energy	169	Passed
ACR126	Seneca Meadows LFG	Landfill Gas Capture & Combustion	2470626	Passed
ACR127	Steuben County DPW LFG	Landfill Gas Capture & Combustion	129180	Passed
ACR128	Streator LFG to Energy	Landfill Gas Capture & Combustion	47150	Passed
ACR129	Tecnosol Solar Electrification	Renewable Energy	3913	Passed

Figure 5.8 : screenshot of the successful registry for projects with unique attributes.

share identical values. The first four projects have the same project type and total credits issued. Hence the system failed the project registry. Clearly, the system's functionality effectively mitigates instances of double counting. as shown in Figure 5.8, the system approved and passed the registry for projects with unique attributes.

5.5 Conclusion

In conclusion, this chapter presents in detail the double-counting sentry, the mechanism built to prevent the double-counting issue in the carbon market. It has the ability to prevent double counting from occurring on two levels: within a single project and across multiple projects. Blockchain technology serves as a powerful tool to tackle these challenges by providing a transparent and secure ledger system for tracking carbon credits.

Addressing the issue of double counting in carbon credit management is imperative for the effectiveness of climate change mitigation efforts.

The next chapter will outline the third research objective of this thesis, which provides an intelligent mechanism to predict the future price of carbon credits based on multiple factors. All the methodological steps involved in crafting the solution are presented in the next chapter.

Chapter 6

Carbon Credit Market Predictive Dynamics

6.1 Introduction

The previous chapter provided an overview of our proposed solution to the double counting issue in the carbon market. This chapter focuses on the first platform components, as briefly mentioned in Chapter 4, to address the third research objective. Specifically, we present an intelligent method aimed at predicting the price of carbon credits, leveraging various factors. In our research, we employ a machine learning algorithm to effectively compute the future price of carbon credits.

This chapter is structured as follows: Section 6.2 provides an in-depth explanation of the methods essential to achieve this objective, encompassing data preprocessing, the chosen dataset, the algorithm employed, and the implementation of our proposed solution. The proposed solution is validated in Section 6.3, while Section 6.4 concludes this chapter.

6.2 Method

This section explores the approach employed for carrying out our research. It overviews the suggested model and the experiment process undertaken to obtain the results from this model. We use mean absolute error (MAE), which represents the average absolute difference between the predicted values and the actual values, to measure the efficiency of our proposed solution (Hyndman and Koehler, 2006). In addition to MAE, we also employ mean squared error (MSE) and the R^2 score to comprehensively evaluate our model's performance. The MSE represents the averaged squared difference between the predicted and actual values, penalising larger errors more severely than smaller ones and thus providing insight into the variability of our model predictions (Ahmar, 2020). The R^2 score, or the coefficient of determination, quantifies the degree to which our model's predictions match the actual values. (Chicco et al., 2021). These metrics offer a holistic view of our model's predictive accuracy and efficiency.

The accuracy of the model directly impacts its utility and reliability in real-world scenarios. By optimising these metrics MAE, MSE, and the coefficient of determination (R^2 score), we aim to enhance the precision and trustworthiness of our predictions, thereby enabling more informed decision making in carbon market analysis and strategy formulation.

A low MAE signifies that the predicted values are close to the actual values, reflecting the model's precision in capturing the underlying patterns in the data. Similarly, a lower MSE indicates that the model's predictions exhibit smaller errors on average, providing further evidence of its accuracy and reliability. Furthermore, a high R^2 score implies that the model explains a significant portion of the variance in carbon prices, indicating its ability to predict future price movements reliably.

By prioritising the optimisation of these metrics, we ensure that our predictive models are equipped to provide actionable insights for stakeholders in the carbon market. Whether it's policymakers crafting regulatory frameworks, investors making strategic investment decisions, or environmental planners designing mitigation strategies, the reliability of our predictions directly influences the effectiveness of their actions. Therefore, our commitment to enhancing the accuracy of our models underscores our dedication to facilitating more effective decision-making processes, ultimately contributing to the sustainability and resilience of the carbon market ecosystem.

6.2.1 Preprocessing

In the realm of contemporary data-driven research, the significance of meticulous data preprocessing cannot be overstated. High-quality data forms the bedrock upon which accurate and reliable results are built, making the preprocessing phase an indispensable precursor to any analytical endeavour.

The integrity of research outcomes hinges on the quality of the input data. As such, the process of refining and cleansing raw data is a critical facet in ensuring the robustness and validity of subsequent analyses. Without diligent preprocessing, the potential for distorted or biased results increases, compromising the overall credibility and applicability of the research findings.

In light of these considerations, this section elucidates the various steps undertaken to refine, clean, and prepare the dataset for meaningful analysis, underscoring the pivotal role of data preprocessing in the pursuit of rigorous and dependable research outcomes.

The selected database

For the purpose of training and testing, we selected a dataset called RCPI-data-public-aug2.xlsx, which is accessible via this link Our choice of this dataset is driven by its relevance to our intended objectives. We focus only on specific columns in the Excel spreadsheet, namely the price, countries (with a specific focus on the USA), and the GHG level (carbon emissions) in line with global policy. These factors play a crucial role in influencing the decision-making process related to the carbon price in our proposed solution. Moreover, once the initial price is determined based on these variables, we further consider the dynamics of supply and demand to establish the ultimate price.

6.2.2 Algorithm

We used machine learning technology to build the solution and used the dataset to test its performance. Then, we represented our result as MAE, MSE and R^2 score metrics.

The pseudo-code: The high-level Algorithm for the carbon credit market predictive dynamics, to compute real-time data based on multiple factors is presented in this section,

function computeRealTimeData (currentPrice, co2EmissionLevel, newRegulation, selectedCountry):

Algorithm 2 high-level Algorithm for the carbon credit market predictive dynamics

Input: currentPrice, co2EmissionLevel, newRegulation, selectedCountry

Output: realTimeData

procedure CALCULATEREALTIMEDATAIMPACT

$priceImpact \leftarrow$ calculatePriceImpact(currentPrice) ▷ Impact of current price

$emissionImpact \leftarrow$ calculateEmissionImpact(co2EmissionLevel) ▷ Influence of CO2 emission level

$regulationImpact \leftarrow$ calculateRegulationImpact(newRegulation) ▷ Effect of new regulations

$countryImpact \leftarrow$ calculateCountryImpact(selectedCountry) ▷ Impact of selected country

$realTimeData \leftarrow$ combineImpacts($priceImpact, emissionImpact, regulationImpact, cou$ ▷ Combine individual impacts

return $realTimeData$ ▷ Return combined real-time data

Our predictive model for global carbon credit prices is a robust tool that considers a range of influencing factors, ensuring a nuanced and accurate forecast. In designing a model for predicting carbon credit prices, integrating factors like CO2 emission levels, historical prices, and new regulations and focusing on specific countries such as the USA enables a comprehensive approach that captures the market's physical and regulatory dimensions. To justify this, CO2 emission levels serve as a direct indicator of carbon credit supply and demand, where higher emissions may increase demand and influence prices, reflecting economic activities and energy consumption patterns vital for forecasting price fluctuations. Historical prices offer insights into market trends and volatility, aiding in the identification of patterns for more accurate short-term forecasts and an understanding of market elasticity. New regulations can drastically alter the market dynamics by impacting the supply-demand balance, making it crucial to monitor regulatory changes, especially in proactive regions like the USA, to anticipate market shifts. Focusing on the USA provides a detailed analysis of regulatory impacts and market responses in a key region, significantly influencing global carbon pricing trends. This multifaceted model approach ensures it remains adaptive to new information, offering actionable insights for a range of stakeholders and facilitating informed decision making by accurately reflecting the market's current state and future direction through a detailed consideration of environmental, economic, and regulatory factors.

6.2.3 Implementation

In the development of our proposed solution, we used the Python programming language to craft the solution's code due to its versatility, extensive libraries, and ease of integration. Leveraging Python facilitates efficient coding practices and supports seamless integration with various data processing and analysis tools.

The core of our solution involves the utilisation of the following seven prediction models: RandomForestRegressor (RFR), Linear Regression (LR), Support Vector Regressor (SVR), Decision Tree (DT), K-neighbour, Ridge Regression and lastly, LASSO regression. This algorithm, a part of the scikit-learn library, is well-suited for regression tasks and achieves robust performance in predicting outcomes based on complex datasets. The processed database, which forms the foundation of our model, undergoes thorough preprocessing to ensure data quality and relevance. This implementation choice aligns with our goal of creating a robust, adaptable, and accurate solution to address the challenges presented by our problem domain.

6.3 Evaluation:

To evaluate the model's accuracy and robustness using the selected dataset, we utilize the following steps:

1. Load and rreview the dataset.
2. Data preprocessing: Prepare the data for modelling, which may include handling missing values, encoding categorical variables, and splitting the dataset into training and testing sets.
3. Model Training: Train the selected prediction models using the training set.
4. Performance Evaluation: Use the testing set to evaluate the model's performance by calculating MAE, MSE, and R^2 score.
5. Comparison with benchmark: Compare these metrics against benchmarks to gauge effectiveness.

6.4 Result and Discussion

The visualizations of each model's predictions against actual carbon prices provide crucial insights into their performance. Figure 6.1 through Figure 6.7 illustrate

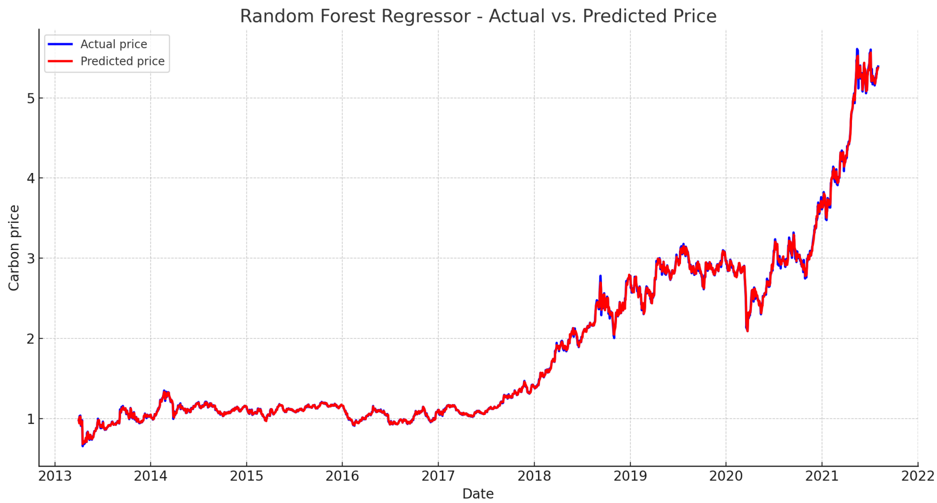

Figure 6.1 : Random forest regressor performance

these comparisons, where the blue line represents the actual carbon prices, and the red line shows the model predictions.

Quantitative metrics such as MAE, MSE, and the R^2 score are as critical as the visual insights from the plots in evaluating carbon price forecasting models. For instance, Figure 6.1 shows that the random forest regressor achieved a close visual match between predictions and actual values with an MAE of 0.0115, an MSE of 0.00035, and an R^2 score of 0.9997. These metrics underscore its exceptional accuracy in capturing the variance in carbon prices, as substantiated by its plot. Figure 6.2 and Figure 6.3 show that the K-Neighbors regressor and the support vector regressor achieved a solid performance, with SVR obtaining an MAE of 0.0545, an MSE of 0.00436, and an R^2 of 0.9963, and K-neighbors achieving an MAE of 0.0233, an MSE of 0.00140, and an R^2 of 0.9988. These models balance simplicity and flexibility, making them suitable for environments where such traits are prioritised. Figure 6.4 illustrates the performance of the decision tree regressor, despite its plot revealing an almost perfect overlay of predicted upon actual values, which might

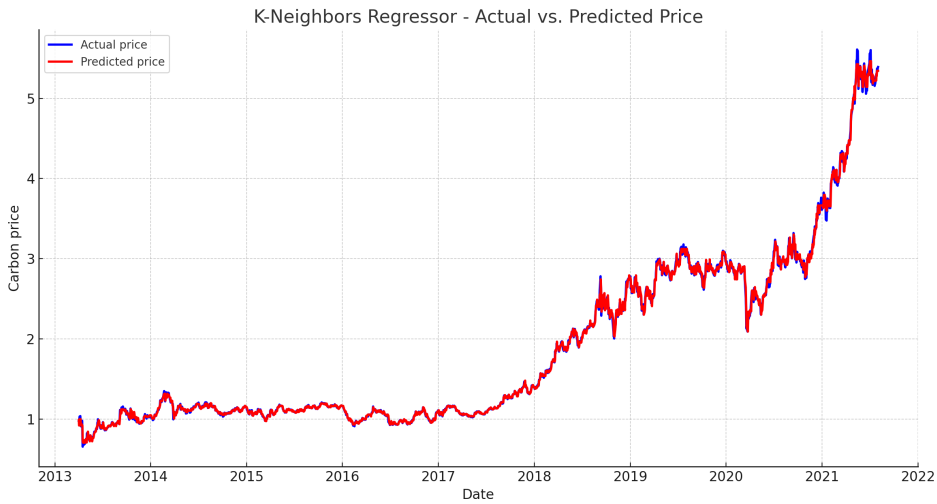

Figure 6.2 : K-neighbors regressor performance.

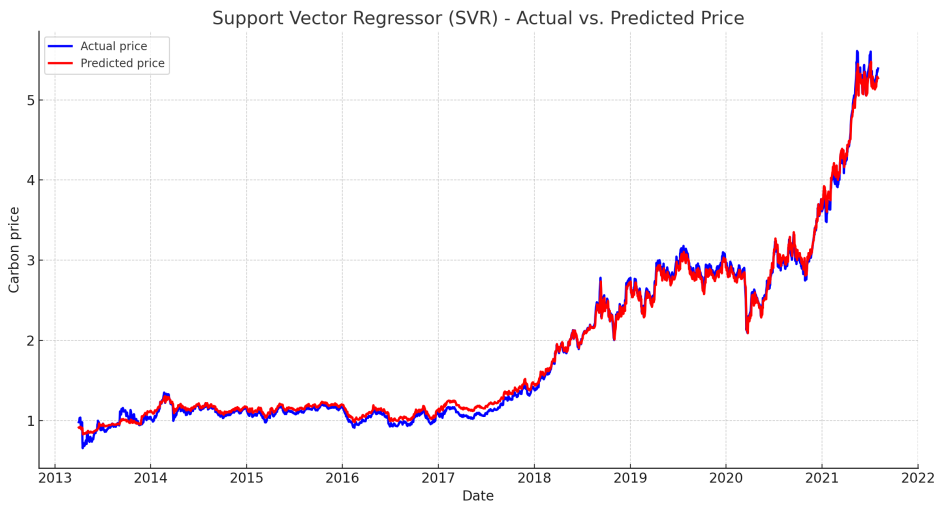

Figure 6.3 : SVR performance.

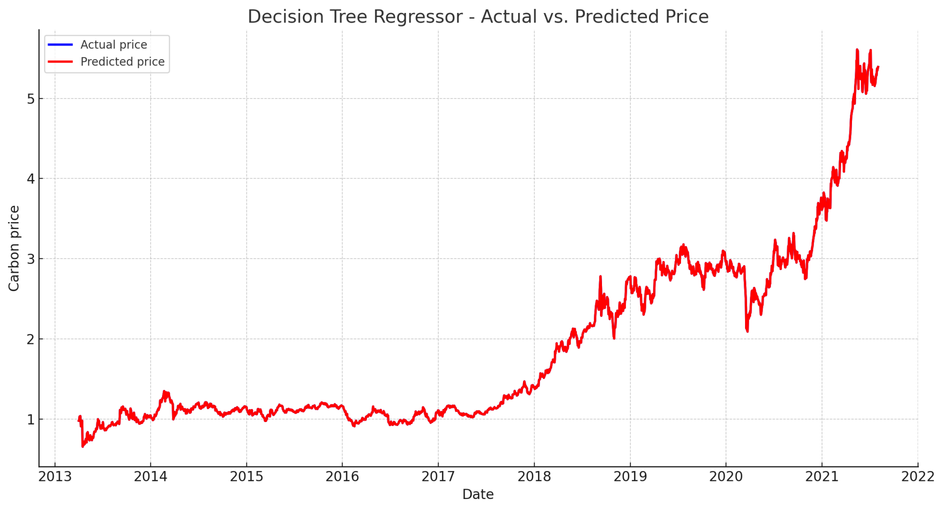

Figure 6.4 : Decision tree performance.

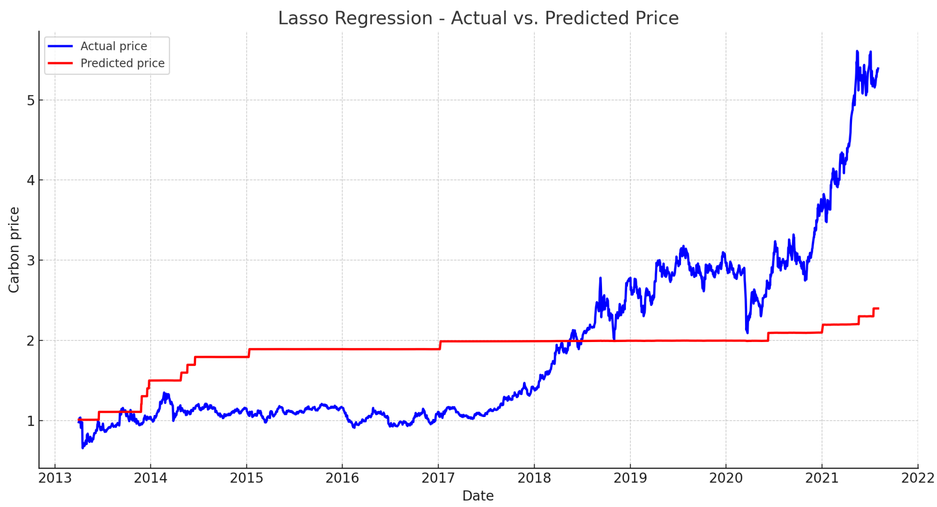

Figure 6.5 : Lasso regression performance.

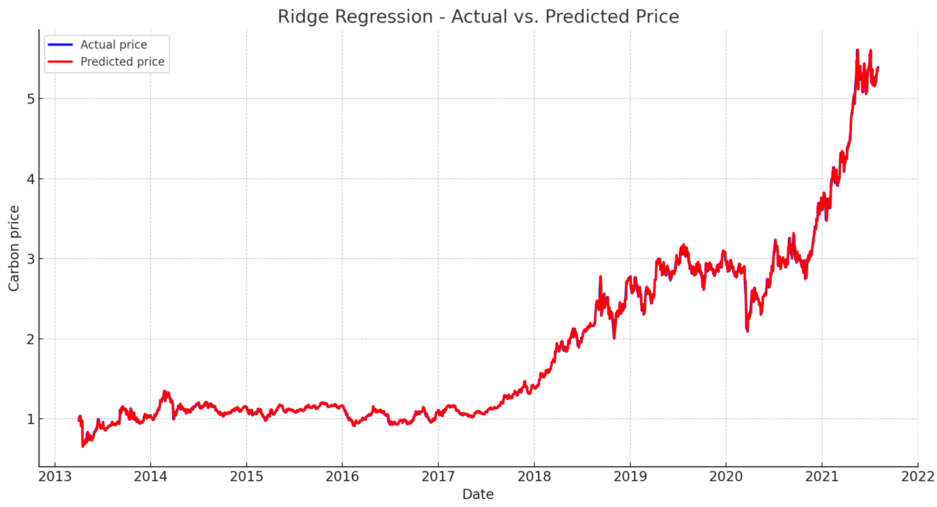

Figure 6.6 : Ridge regression performance

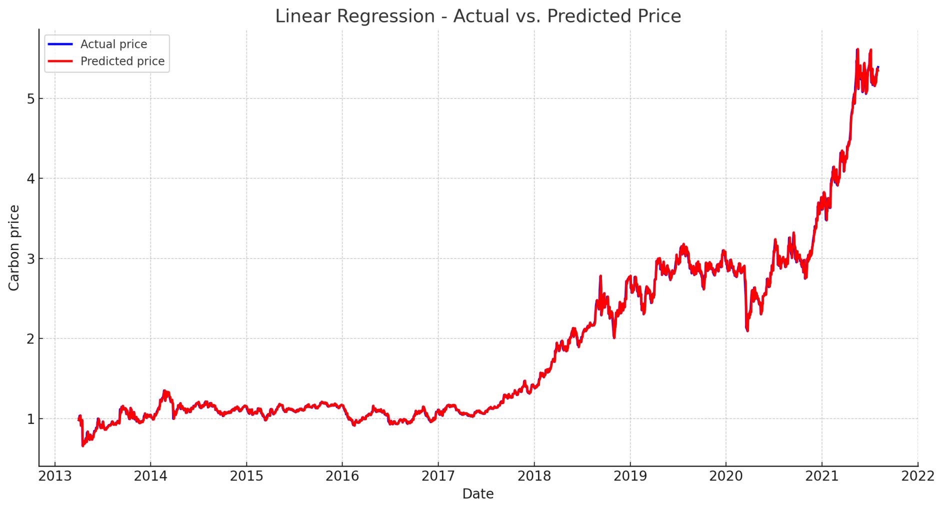

Figure 6.7 : Liner regression performance.

suggest impeccable performance, attains an R^2 score of nearly 1 and negligible MAE and MSE values. This level of perfection raises practical concerns about overfitting, indicating that the model may not generalise well to unseen data. Conversely, the ridge regression and linear regression models, as shown in Figure 6.6 and Figure 6.7, respectively, achieved MAE values of approximately 0.0257 and 0.0258 and MSE values of around 0.00175 for both, along with R^2 scores of 0.9985, offering a practical compromise. The plots for these models show a slight deviation from the actual carbon prices, reflecting these error metrics and affirming their role as interpretable and computationally efficient options. In stark contrast, the plot of the lasso regression model in Figure 6.5, clearly demonstrates its poorer performance with a high MAE of 0.7748, a very high MSE of 0.9009, and a low R^2 score of 0.2393. This model's penalisation seems to compromise its ability to accurately forecast carbon prices, as reflected in its plot's larger errors and the substantial deviation.

A comparison of the results after evaluating each model is presented in Table 6.1 for clarity.

Model	**Mean Absolute Error (MAE)**	**Mean Squared Error (MSE)**	**R^2 Score**
Random Forest	0.0115	0.00035	0.9997
Linear Regression	0.0257	0.00175	0.9985
Ridge Regression	0.0258	0.00175	0.9985
Lasso Regression	0.7748	0.9009	0.2393
Decision Tree	2.3851095764273068e-06	6.177979993039858e-09	0.99999999
SVR	0.0545	0.00436	0.9963
K-Neighbors	0.0233	0.0014	0.9988

Table 6.1 : Performance comparison of various models

This table highlights the variance in performance across the different models. The decision tree regressor achieves nearly perfect scores, indicating an extremely close fit to the training data, which might suggest overfitting. On the other hand, models like the random forest regressor and K-neighbors regressor also perform extremely well but with slightly more realistic metrics that suggest a good balance between fit and generalisation. The lasso regression model achieves significantly lower performance than the other models, so we disregard it. Given the high R^2 score and low error metrics, the random forest regressor seems to be the best model of those evaluated in this study.

6.5 Conclusion

This chapter has comprehensively explored an intelligent method tailored for predicting the price of carbon credits, integrating various influential factors. The proposed solution, underpinned by machine learning, demonstrates exceptional performance, as evidenced by a remarkably low MAE of 0.0115 for the Random Forest regressor. This outstanding accuracy positions the model as a reliable tool for various stakeholders, offering valuable insights for strategic planning, financial decision support, and sustainability initiatives.

The following chapter meticulously outlines how the fourth research objective of this thesis is addressed, which involves the development of the carbon credits trading marketplace. We detail the methodological steps involved in developing and testing this solution and elaborate on its significance.

Chapter 7

The Green Credits Hub - A Marketplace for Carbon Credits

7.1 Introduction

The preceding chapter overviewed the proposed solution to provide an accurate prediction tool for the price of carbon credits. This chapter provides a detailed explanation of our proposed solution for the carbon credits trading marketplace to address the fourth research objective. The chapter is structured as follows: section 7.2 explores the Green Credit Hub, section 7.3 discusses the Registration Mechanism, section 7.4 focuses on the Trading Mechanism, section 7.5 outlines the Marketplace Workflow, section 7.6 covers Implementation and Results, section 7.7 involves Discussion, and section 7.8 concludes the chapter.

7.2 The Green Credit Hub

Figure 7.1 illustrates the Green Credit Hub, highlighting its two main parts: the registration and trading mechanisms. The registration mechanism encompasses four various registration types: user registration, verifier registration, credit holder registration, and carbon credits registration. There is a specific way for each group to join the hub. Section 7.3 provides details on how this registration process works.

For trading, the hub allows users to sell, buy, be informed about the predicted price, and look after their profiles. This shows that the hub is not just for buying and selling credits but also helps users guess future prices and manage their information. Section 7.4 provides more details on how trading works to make it easy for users to

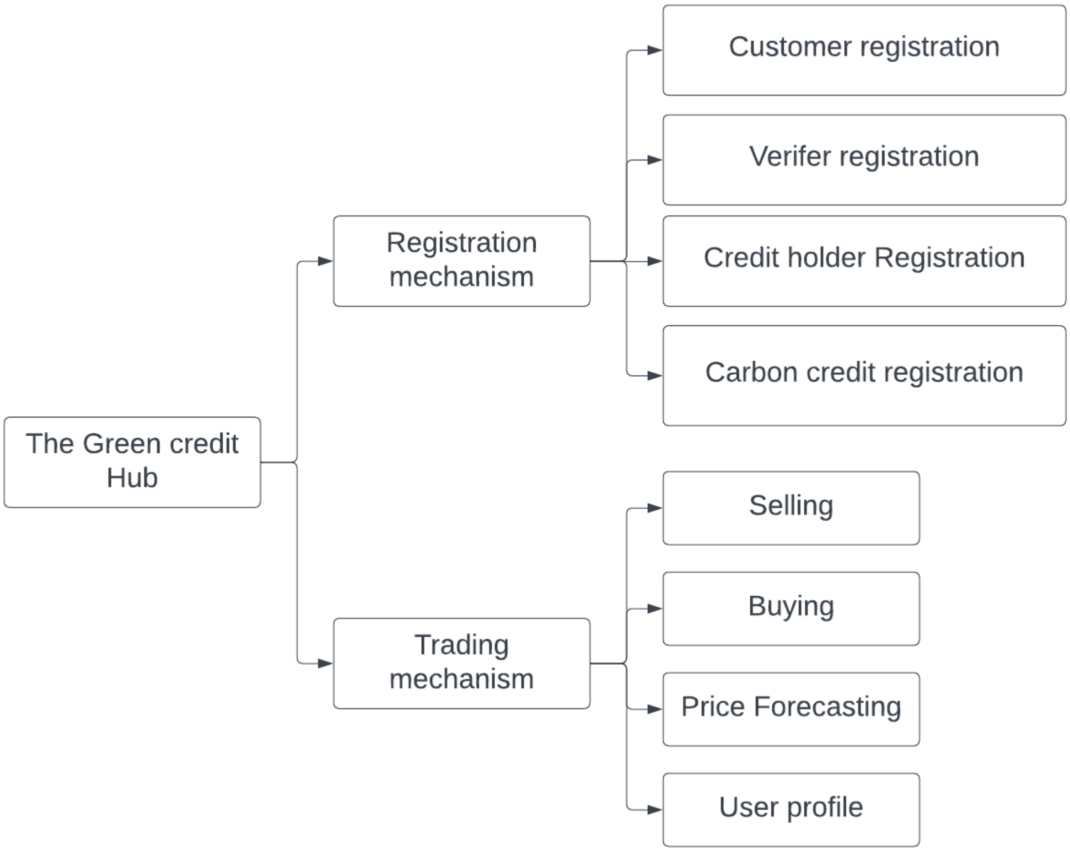

Figure 7.1 : The Green Credit Hub

transact, understand the market, and manage their accounts.

7.3 The Registration Mechanism

In a carbon credit trading marketplace, a detailed registration procedure upholds the integrity, transparency, and efficiency of transactions. Figure 7.2 illustrates the registration process for four user categories, each designed with unique requirements that align with their specific role in the ecosystem.

1. **Customer Registration:** Clients seeking to engage in carbon credits trading must undergo registration, providing essential personal details such as full name, email address, and contact number. Upon completion, a unique identi-

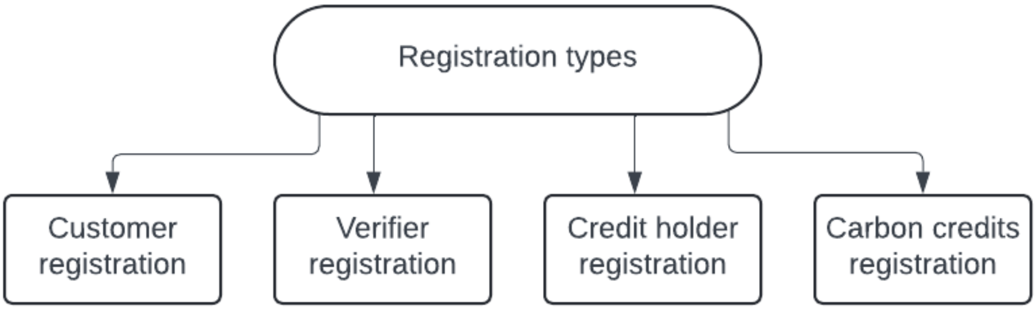

Figure 7.2 : Registration Types

Figure 7.3 : Customer registration

fier is generated, granting access to the platform's features and functionalities. Figure 7.3 illustrates a screenshot of the customer registry.

2. **Verifier Registration:** Verifiers play a pivotal role in maintaining the accuracy of information in the marketplace. During registration, verifiers submit key information, including their full name, country of residence, verifier registration number, and verifier license number. A unique identifier is assigned upon successful registration, serving as a primary linkage between the verifier and carbon credits in the verification process. Figure 7.4 illustrates the verifier

Figure 7.4 : Verifier registration

registry.

3. **Credit Holder Registration:** Individuals or entities possessing carbon credits must register as credit holders to manage and trade their assets effectively. Registration entails providing details such as the credit holder's name, full address, and type of credit holder. Figure 7.5 shows the credit holder registration. A unique identifier is generated upon registration completion, facilitating seamless linkage between the credit holder and their carbon credits, ensuring ownership rights and validity.

4. **Carbon Credit Registration:** Carbon credits, the tangible assets within the marketplace, undergo individual registration by their holders. Details, including the number of carbon credits, issue date, and issue authority, are submitted for registration as illustrated in Figure 7.6. Subsequently, the application undergoes verification by a designated verifier, who either approves or rejects the application based on the provided information. Verified details are then securely stored on the blockchain, ensuring transparency and reliability in the trading process. Figure 7.6 shows the verification process, and

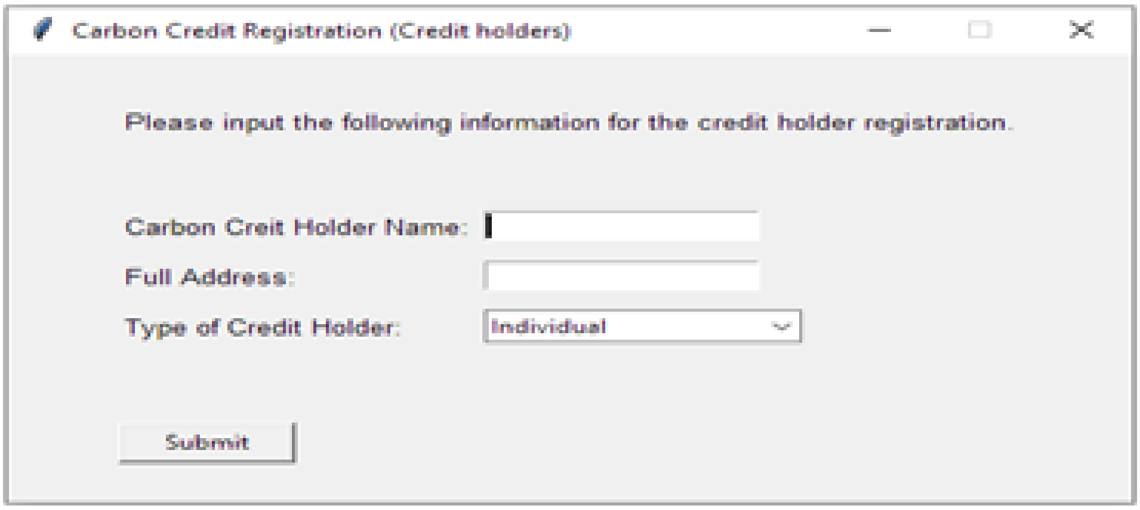

Figure 7.5 : Credit holder registration

Figure 7.7 shows the registration state after verification.

Incorporating blockchain technology into the registration process further enhances security and trust, as all registered information is immutably recorded on the blockchain. This comprehensive registration framework establishes a robust foundation for carbon credit trading, fostering a marketplace characterised by accountability, credibility, and sustainable environmental impact.

In this carbon credits trading marketplace, participants partake in a comprehensive ecosystem designed to facilitate the seamless selling and purchasing of carbon credits. Additionally, the platform offers sophisticated tools for accurate price forecasting and empowers users with the ability to create and manage their profiles efficiently. Serving as a central hub for environmentally conscious trading, this marketplace enables active engagement in carbon offsetting initiatives while providing robust transaction management capabilities and insightful forecasting tools.

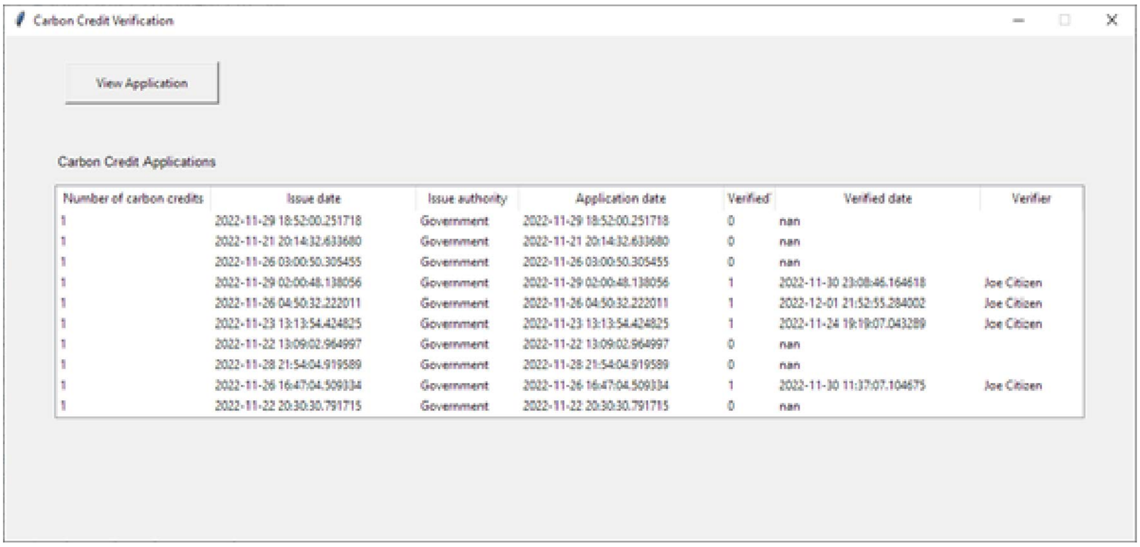

Figure 7.6 : Verification process

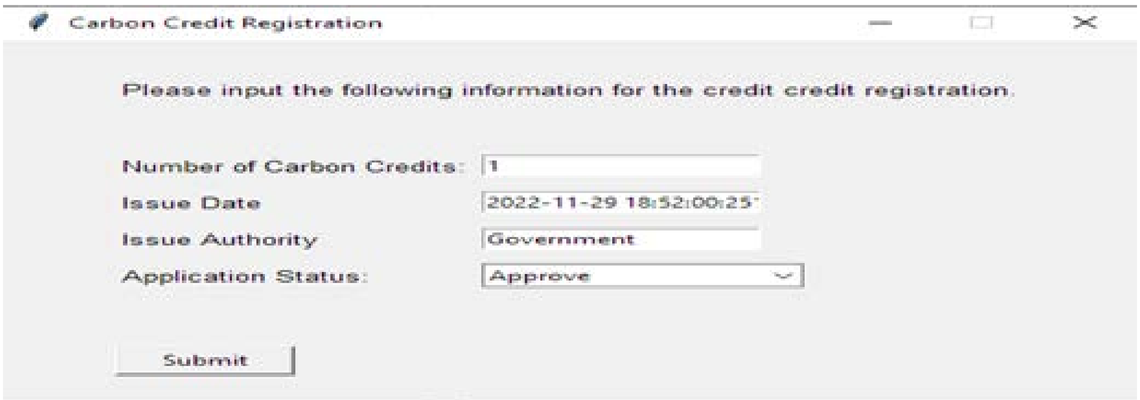

Figure 7.7 : State after verification

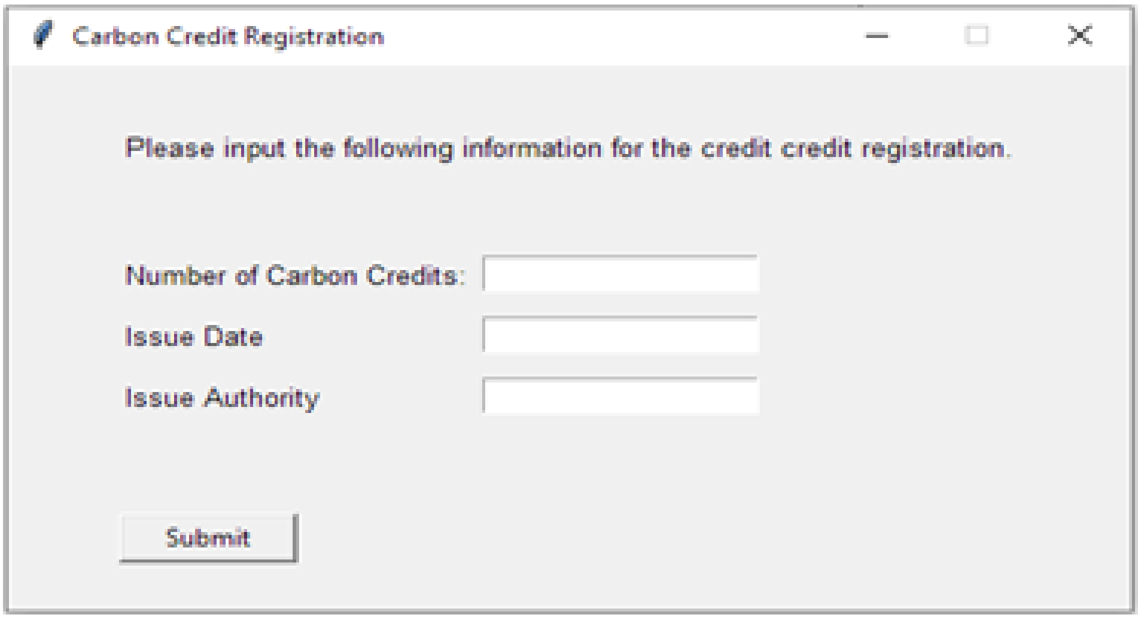

Figure 7.8 : Carbon credit registration

7.4 The Trading Mechanism

In this carbon credits trading marketplace, participants engage in a comprehensive ecosystem that facilitates the selling and buying of carbon credits, offers tools for price forecasting, and allows for the creation and management of user profiles. This marketplace is a hub for environmentally conscious trading, enabling users to actively participate in carbon offsetting initiatives while managing their transactions and forecasts efficiently. Figure 7.9 illustrates the marketplace interface listing the four features. The marketplace encompasses the following four key activities:

1. **Selling Feature:** Users can easily list their available carbon credits for sale, streamlining the process of connecting sellers with potential buyers in the platform's marketplace.

2. **Buying Feature:** Facilitating the purchasing process, this feature allows users to browse available carbon credits and make purchases according to their specific needs and sustainability goals.

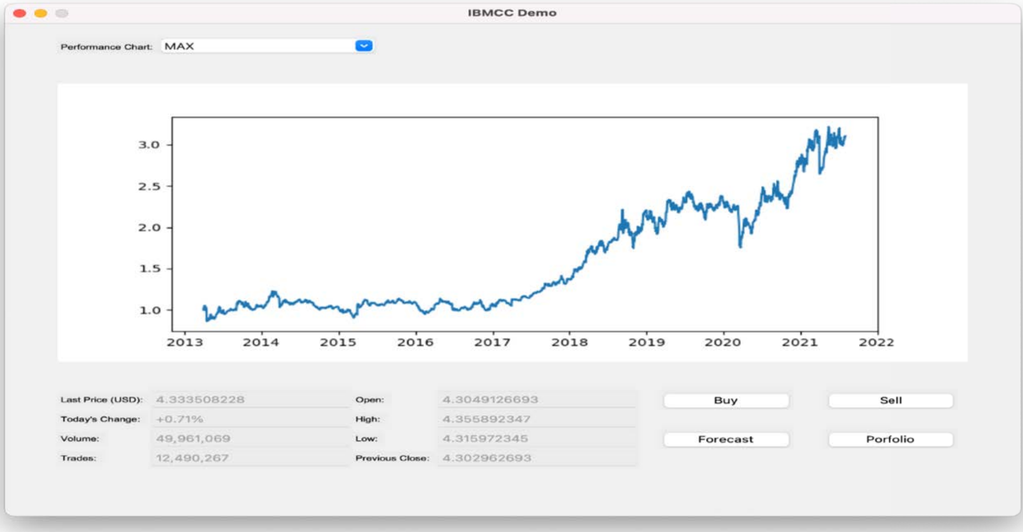

Figure 7.9 : The marketplace interface

3. **Price Forecasting Feature:** Leveraging advanced algorithms and data analytics, this feature provides users with valuable insights into future carbon credit prices, enabling informed decision making and strategic planning.

4. **User Profile Feature:** This feature empowers users to create and manage personalized profiles, fostering a sense of community within the marketplace while facilitating transparent communication and networking among participants. Users can showcase their sustainability initiatives, track their trading activities, and connect with like-minded individuals and organisations.

7.4.1 Sell Feature

The sell feature allows end users to do the following:

- Sellers can easily list their carbon credits on the platform by creating a seller account and providing relevant information about their credits, such as the type, quantity, and verification status.

- It allows sellers to input data through an intuitive interface and upload supporting documentation to validate the authenticity of their credits.
- Smart contracts are pivotal in facilitating secure transactions between buyers and sellers.
- Upon agreeing to the transaction terms, smart contracts automatically execute the transfer of carbon credits from the seller to the buyer once payment is confirmed.

The following steps enable a user to place a sell order for carbon credits on the platform:

1. Create a seller account on the platform.
2. Provide detailed information about the carbon credits you want to sell, including type, quantity, and verification status.
3. Use the platform's intuitive interface to input data.
4. Select your account from the dropdown menu.
5. Review the Units Available field to see how many credits you have available for sale.
6. Enter the number of carbon credits you want to sell in the Quantity field.
7. Specify the value per unit in the Value field.
8. If desired, set a price limit in the Price Limit field.
9. The Order Value field will calculate the total value of the sale based on the entered quantity and value per unit.
10. Review any fees or commissions included in the Brokerage & Cost field.

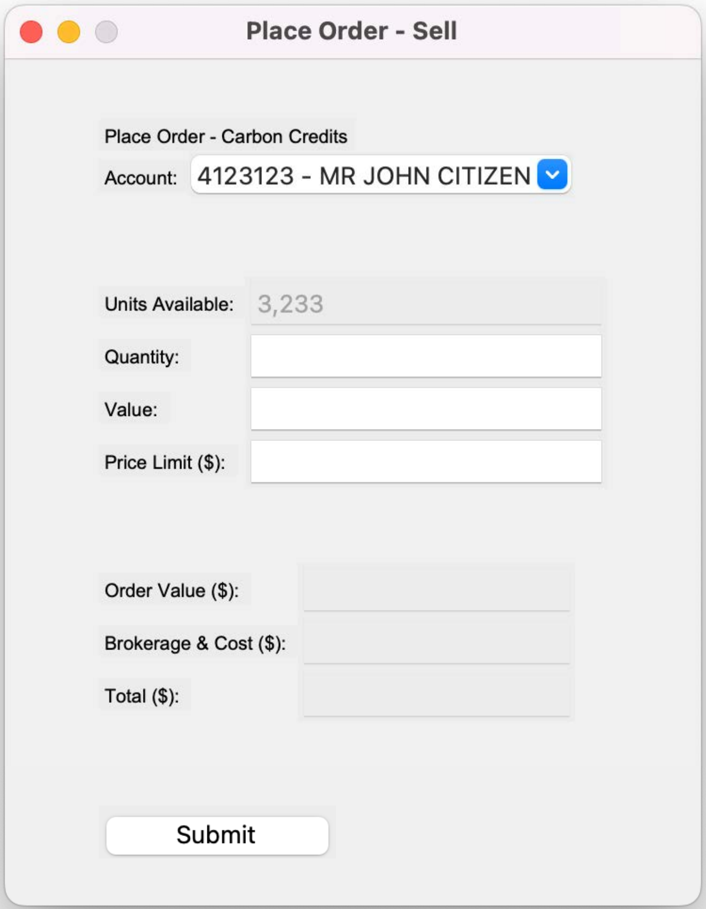

Figure 7.10 : Sell feature

11. Check the Total field to see the final amount you will incur post-deductions.

12. Click the Submit button to place your sell order for the carbon credits.

Figure 7.10 shows a screenshot of the place order (sell) feature in the marketplace.

7.4.2 Buy Feature

The buy feature allows the end user to do the following:

- Buyers can easily browse through the available carbon credits listed on the marketplace.
- Once buyers find suitable credits, they can initiate the purchase process with a simple click, triggering the execution of the transaction through smart contracts.
- Buyers can trace the history of carbon credits back to their origin, providing assurance of their environmental integrity and compliance with regulatory standards.
- Upon completion of a transaction, funds are transferred directly from the buyer's account to the seller's account through the blockchain.

The steps to place a sell order for carbon credits on the platform are as follows :

1. Log into your seller account on the platform.
2. Choose the option to buy carbon credits.
3. Select your account from the dropdown menu.
4. Enter the quantity of carbon credits you wish to buy.
5. Specify your bid value per carbon credit.
6. Set your price limit for the purchase, if applicable.
7. Review the automatically calculated order value.
8. Acknowledge the brokerage and cost fees.
9. Check the total amount to be paid.
10. Submit your buy order.

Figure 7.11 displays a screenshot of the place order feature in the marketplace.

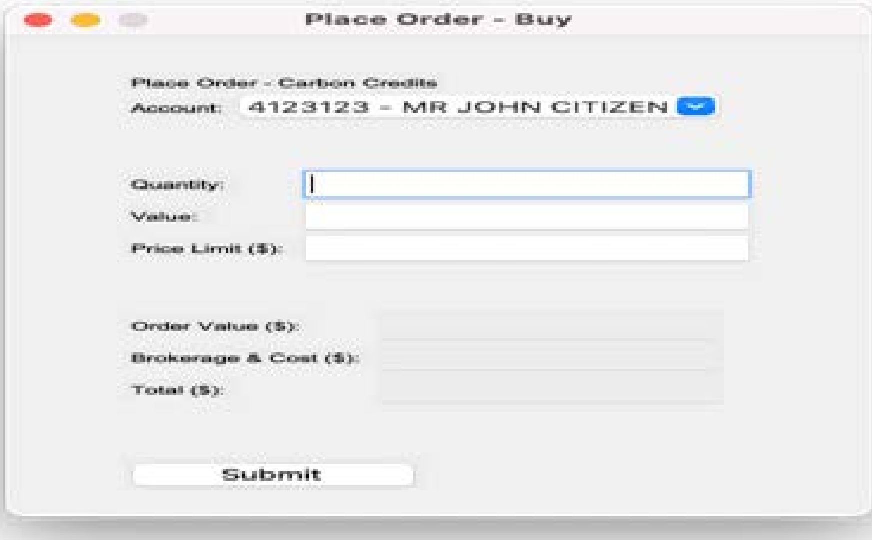

Figure 7.11 : Buy feature

7.4.3 Price Forecasting Feature

The price forecasting feature of the marketplace offers the following benefits:

1. It helps market participants make informed decisions about buying, selling, and holding carbon credits.
2. Participants can optimise their trading strategies, maximise their returns, and mitigate the risks associated with price volatility.
3. Participants can forecast carbon credit prices accurately by employing sophisticated algorithms and analytical machine-learning techniques
4. By continuously updating and refining their models, the marketplace can adapt to changing market conditions and provide up-to-date price forecasts for market participants.

Figure 7.12 provides a screenshot of price forecasting in the marketplace. The

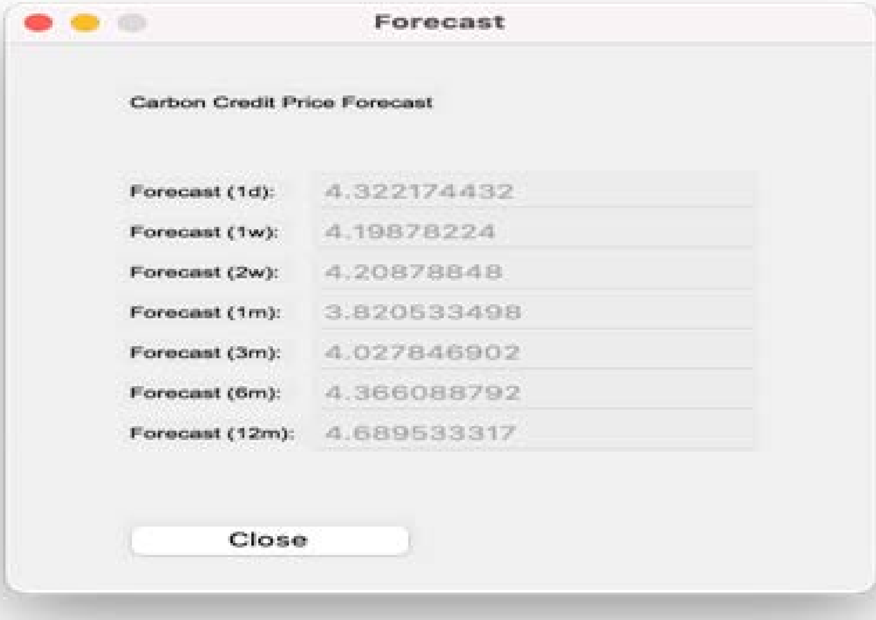

Figure 7.12 : Price forecasting feature

way the price is predicted is discussed in detail in Chapter 6 of this thesis.

7.4.4 Profile Feature

The profile feature offers the following benefits:

1. User profiles are integral to the marketplace, providing a centralised platform for users to manage their accounts, track their transactions, and engage with other participants.
2. Each user profile contains essential information about the user, such as their contact details, transaction history, and preferences.
3. User profiles enhance trust and transparency in the marketplace by providing visibility into users' identities and credentials.

Figure 7.13 : Profile feature

4. The marketplace implements robust privacy and security measures to protect user data and ensure compliance with data protection regulations.
5. Personal information is encrypted and stored securely, with access restricted to authorised users only.

Figure 7.13 shows a screenshot of the user profile feature.

7.5 The marketplace workflow:

The marketplace workflow comprises several key stages, each tailored to facilitate seamless interaction between users and the platform. Figure 7.14 illustrates the steps of the marketplace workflow.

1. User Registration: The process begins with users initiating interaction with the IBMCC platform by completing the user registration process. This step

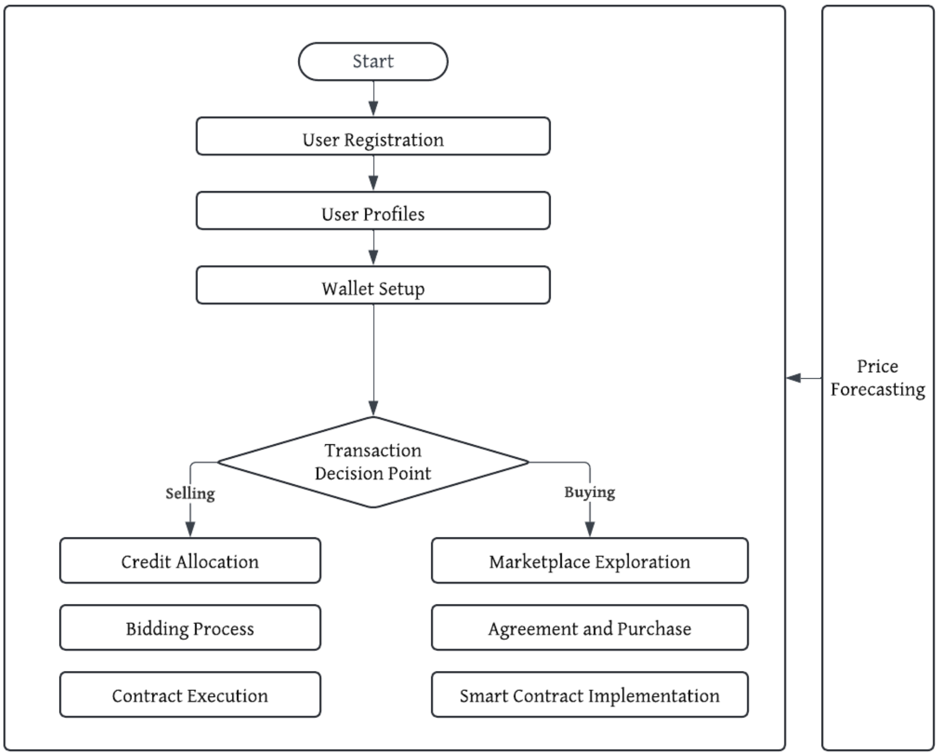

Figure 7.14 : The marketplace workflow.

ensures that users are onboarded securely and provided with access to the marketplace functionalities.

2. Wallet setup: Upon registration, users are prompted to establish a digital wallet, which serves as the primary instrument for conducting carbon credit transactions. This digital wallet is essential for securely storing and managing users' carbon credits and facilitating transactions within the marketplace.

3. Transaction Decision Point: Users are presented with the option to choose between purchasing or selling carbon credits. The user interface guides users to the relevant marketplace functionality based on their transaction preferences, ensuring a seamless and intuitive user experience.

4. - **If selling carbon credits:**

   4a. Credit Allocation: Sellers initiate the process by transferring their carbon credits from their digital wallet to the marketplace. This step ensures that sellers have the necessary credits available for listing and sale within the platform.

   4b. Bidding Process: Sellers have the option to allow consumers to bid on their carbon credits, thereby maximizing the potential value of their assets. Sellers can review and select a winning bid based on their preferences and market dynamics.

   4c. Contract Execution: Upon selecting a winning bid, sellers execute the sale through a smart contract, which facilitates the secure transfer of credit ownership to the buyer. This ensures that the transaction is executed transparently and immutably on the blockchain.

5. -**If buying carbon credits:**

   5a. Marketplace Exploration: Buyers navigate the marketplace to explore available carbon credits, utilizing search and filtering functionalities to identify suitable assets. This step allows buyers to evaluate different options and make informed purchasing decisions.

5b. Agreement and Purchase: Once a suitable carbon credit is identified, buyers agree to the terms and conditions of the transaction and proceed to purchase the credits. This step ensures that buyers are aware of the conditions associated with the transaction and consent to the purchase.

5c. Smart Contract Implementation: The purchase is finalized through the implementation of a smart contract, which ensures secure transaction recording on the blockchain. This ensures that the transaction details are recorded transparently and immutably, providing assurance to both buyers and sellers.

6. Price Forecasting: The marketplace incorporates a price forecasting feature, enabling users to access predictions of future carbon credit prices. Utilizing historical data and predictive algorithms, the marketplace generates accurate forecasts, empowering users to make informed decisions regarding buying, selling, and holding carbon credits.

7. User Profiles: The marketplace provides users with personalized profiles, allowing them to manage their accounts, track transactions, and engage with other participants. User profiles enhance trust and transparency within the marketplace by providing visibility into users' identities, transaction history, and preferences. Robust privacy and security measures are implemented to protect user data and ensure compliance with data protection regulations.

The utilization of Ethereum blockchain and smart contracts enables transparent, secure, and auditable transactions, fostering trust and integrity within the marketplace ecosystem.

7.6 Implementation and Results

The primary aim of engineering the prototype system is to simulate the working of the marketplace, an intelligent framework that trades carbon credits. Our objective is to use the developed prototype to test the efficacy of the marketplace process of the system to achieve the third objective of this thesis. To implement the prototype, we use Ganache, an Ethereum simulator that makes developing Ethereum applications faster, easier, and safer. It includes all the popular RPC functions and features and can be run deterministically to make development easy. Ethereum was introduced in 2013 and is one of the oldest and most established blockchain platforms. It provides a truly decentralised blockchain. Along with Ethereum, we also utilized Python scripts in the implementation phase for off-chain functionality integration, including data processing and user interface development. Rigorous testing ensured functionality, security, and scalability. the results confirmed the effectiveness of the marketplace, fostering transparent, secure, and efficient carbon credit trading. With Ethereum and Python, the marketplace offers a flexible solution and is anticipated to have a positive impact in combating climate change.

7.7 Discussion

The marketplace trading platform offers a comprehensive suite of features designed to revolutionise carbon credit trading and drive sustainability efforts forward. At its core, the platform leverages cutting-edge technologies such as distributed ledger technology and smart contracts to ensure transparency, efficiency, and trust in transactions.

Transparency is a cornerstone of the platform, achieved through a transparent ledger system that records all transactions related to carbon credits. Each transaction is timestamped and cryptographically secured, providing participants with a clear and immutable record of the credit's history. This transparency fosters trust and accountability in the marketplace, empowering participants to verify the authenticity of credits with ease.

Smart contracts automate and enforce the terms of carbon credit transactions, streamlining processes and reducing administrative overhead. This not only enhances efficiency but also ensures transactions occur in a transparent and trustless manner. Additionally, smart contracts facilitate the verification process, further bolstering confidence in the marketplace.

Decentralization is another key feature of the platform, enabling direct interaction and transactions between buyers and sellers without the need for intermediaries. This peer-to-peer trading model reduces transaction costs and increases accessibility for smaller market participants, promoting inclusivity and democratizing access to carbon markets.

The platform integrates a robust verification mechanism to ensure the integrity and validity of the carbon credits traded. Third-party auditors and validators verify emission reduction projects and validate the issuance of carbon credits, providing buyers with confidence in the authenticity of credits purchased.

In addition to these features, the platform incorporates price forecasting mechanisms to provide insights into future carbon credit prices. By leveraging data analytics and predictive modeling, participants can make informed decisions regarding their trades, mitigating risks and optimizing their trading strategies.

Complementing these technological features is a sophisticated user profiling system that tailors the trading experience to the unique needs and preferences of individual participants. Through comprehensive user profiles, the platform delivers personalized recommendations, fosters community engagement, and ensures compliance with regulatory requirements.

Together, these features create a dynamic and inclusive marketplace trading platform that accelerates the adoption of sustainable practices and contributes to global efforts to combat climate change. By putting transparency, efficiency, and user empowerment at the forefront, the platform drives positive environmental outcomes while fostering a more sustainable future for all.

7.8 Conclusion

In conclusion, this chapter presents a novel approach to improving carbon credit trading through the development of a blockchain-based marketplace. By leveraging blockchain technology, the marketplace offers enhanced efficiency, transparency, and trust, thereby addressing key challenges faced by traditional carbon trading systems. The features of the marketplace, cater to the diverse needs of stakeholders and facilitate a more inclusive and sustainable carbon trading ecosystem.

The next chapter concludes the thesis and provides a background for future research work.

Chapter 8

Conclusion

8.1 Introduction

This chapter concludes the thesis, providing a summary of the research discoveries and offering suggestions for future research. While numerous researchers have explored the intersection of blockchain and carbon credits, this thesis represents a pioneering endeavour by leveraging blockchain and artificial intelligence technologies to develop an intelligent blockchain-based carbon credit management and trading system. The need for this pioneering effort is highlighted in Chapter 2, where the results of a comprehensive review of the existing literature and an in-depth analysis of previous research are presented. Through these investigations, critical research gaps were identified, prompting the development of a novel solution known as the IBMCC platform to address these gaps.

8.2 Problems Addressed in this Thesis

This section details the specific problems addressed by this thesis. Through a detailed examination, we highlight the key challenges confronted and the innovative solutions proposed to surmount them. The main objective of this thesis is to address significant gaps concerning the utilization of blockchain technology in carbon trading and management in the current literature. Drawing from the literature review in Chapter 2, the research identified and subsequently tackled the pertinent research issues including the following:

1. None of the existing literature develops an intelligent, trustworthy, and global

platform for managing and trading carbon credits.

2. None of the existing literature develops an intelligent mechanism to predict the future price of carbon credits based on multiple factors.

3. None of the existing literature developes a mechanism to prevent the double counting problem in carbon credits at the project level before it occurs (from the source) or even within the project itself.

4. None of the existing literature develops a marketplace mechanism based on blockchain that enables the stakeholders to trade carbon credits in a reliable manner.

8.3 Contributions to Existing knowledge

8.3.1 Systematic Literature Review

Chapter 2 of the thesis effectively documents an extensive and systematic review of the existing literature in the fields of blockchain and carbon credits, providing a comprehensive state-of-the-art overview. Specific search terms were input into the following databases for the systematic literature review:

- IEEE Xplore. (www.ieexplore.ieee.org/Xplore/),
- Elsevier ScienceDirect. (www.sciencedirect.com/),
- ACM. (https://www.acm.org/),
- SringerLink. (https://link.springer.com/),
- Scopus. (https://www.scopus.com/home.uri),
- Web of Science. (https://www.webofscience.com > wos)
- Google Scholar. (www.scholar.google.com.au/),

Inclusion and exclusion criteria were applied to the results of the search process and they were evaluated for relevance. Following the evaluation, 28 pertinent papers were identified and critically reviewed. The review revealed that none of the existing literature has developed a framework to facilitate the management and trading of carbon credits. At the time of writing this thesis, we have drafted a journal paper documenting the systematic literature review. It has been submitted to the Journal of International Journal of Web and Grid Services and is presently under review.

8.3.2 Development of an Innovative Solution: The IBMCC Framework

This study introduces and constructs an innovative framework, IBMCC, designed to address the challenges within the carbon market. Built upon blockchain technology, this framework consists of three interconnected layers, each serving a crucial role in achieving the platform's objectives. The intelligence layer embedded in the platform incorporates automated and dependable mechanisms, ensuring the following:

It prevents the double counting issue in carbon credits

The double counting sentry offers a solution to prevent the issue of double counting across multiple projects and within a single project. By utilizing the Ethereum blockchain, this mechanism ensures transparency and integrity throughout the entire process. Each project registered in any registry is recorded as metadata in the blockchain ledger. When a new project is added to any registry, the system cross-checks existing records to confirm whether the project is already listed elsewhere. This proactive approach tackles the double counting problem at its source, preventing such issues from occurring across different projects.

To further address double counting within individual projects, we have introduced the Carbon Credits Unique Identifier (CCUI) system. This mechanism assigns a unique ID to each carbon credit issued, ensuring no credit is counted more than once. These combined measures improve the accuracy and accountability of carbon credit management, ensuring robust tracking within the carbon market.

End users, such as businesses or individuals purchasing carbon credits, can trust that the credits they acquire represent actual reductions in carbon emissions. The blockchain-based verification process and the unique identifier system prevent fraudulent claims, fostering confidence that their contributions are supporting legitimate environmental initiatives. This reinforces trust and ensures effective climate action.

At the time of writing this thesis, we have drafted a journal paper documenting the Double counting sentry to be submitted to the Journal of Internet of Things.

It predicts the future price of carbon credits based on multiple factors

To meet the objective of predicting carbon credit prices, we integrated an intelligent mechanism into our platform that autonomously considers multiple dynamic factors. These factors, which are constantly changing, are used to forecast future prices in the carbon credit market. Our predictive model is based on the Random Forest Regressor, known for its accuracy in predicting continuous outcomes.

The model takes into account variables such as current carbon credit prices, CO2 emission levels, evolving regulatory frameworks, and country-specific contexts. This comprehensive analysis enables us to provide more accurate and adaptable price forecasts for the global carbon credit market.

With these predictions, businesses can plan their environmental strategies and financial commitments with greater certainty. They can make more informed decisions about when to buy carbon credits, optimizing costs and staying ahead of market fluctuations. This helps ensure compliance with environmental regulations while effectively managing sustainability budgets.

At the time of writing this thesis, we have published a conference paper documenting the carbon credits price prediction model. It has been published in the AINA 2024 conference.

It provides a secure trading marketplace for carbon credits

We developed the Green Hub, a marketplace designed to streamline carbon credit trading. This platform facilitates the buying and selling of carbon credits, offering a space for holders to engage in secure transactions. Built with an emphasis on public accessibility, decentralization, and trust, the marketplace enhances transparency and integrity in carbon credit exchanges. By operating on a blockchain-based platform, the Green Hub ensures that transactions are secure, verifiable, and free from fraud, promoting sustainability efforts in the fight against climate change.

For businesses seeking to offset emissions or participate in sustainability projects, the Green Hub simplifies the process, making it more reliable and efficient to engage in the carbon market. By fostering a secure and transparent marketplace, this platform contributes to global environmental efforts. At the time of writing this thesis, we have drafted a journal paper documenting the Green Hub, a marketplace for trading carbon credits to be submit to the Journal of Knowledge-based Systems.

8.3.3 Evaluation, Validation, and Implementation of the Proposed Solutions

To validate the performance and accuracy of the proposed platform outlined in this thesis. we employed software prototyping as the model of choice. The functionality of the prototype is illustrated in Chapters 5-7, each corresponding to a specific objective.

8.4 Future Work

Despite the thorough exploration conducted in this study on employing blockchain for carbon credits management and trading systems, there remain further avenues for investigation in the future. Our forthcoming endeavours will be directed towards the following:

1. One recommended area for future work is the development of this system into a genuine marketplace. In this research, the framework was created, conceptualized, and a prototype was constructed. While the current system remains a prototype and not yet a real-world application, it has the potential to evolve into a profitable venture by utilizing the IBMCC architecture. However, significant technological challenges, along with other issues, will need to be addressed when developing this solution for real-world use.

2. The proposed model for predicting future carbon credit prices initially focuses on the United States as a key influencing factor. However, to improve predictive accuracy and gain a more comprehensive understanding of global factors, future research should expand the analysis to include data from other countries. While the current model is based on a small dataset limited to the U.S., future research should involve a much larger, real-world dataset. This may require the use of advanced techniques, such as deep neural networks, to handle the increased complexity of the data.

3. To explore the system's potential further, future research could investigate its application to social carbon. This extension may provide valuable insights into the broader societal impacts of carbon offset projects. However, implementing such a solution would present several technological challenges, including selecting the appropriate blockchain platform for social carbon and determining an accurate pricing model.

Bibliography

Ahmar, A. S. (2020). Forecast error calculation with mean squared error (mse) and mean absolute percentage error (mape). *JINAV: Journal of Information and Visualization*, 1(2):94–96.

Al Sadawi, A., Madani, B., Saboor, S., Ndiaye, M., and Abu-Lebdeh, G. (2020). A hierarchical blockchain of things network for unified carbon emission trading (hbuets): a conceptual framework. In *2020 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD)*, pages 1–7. IEEE.

Al Sadawi, A., Madani, B., Saboor, S., Ndiaye, M., and Abu-Lebdeh, G. (2021). A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract. *Technological Forecasting and Social Change*, 173:121124.

Al Sadawi, A. and Ndiaye, M. (2021). Blockchain-based carbon trading mechanism to elevate governance and smartness. In *Proceedings of the 14th International Conference on Theory and Practice of Electronic Governance*, pages 34–43.

Bai, Y., Song, T., Yang, Y., Bocheng, O., and Liang, S. (2020). Construction of carbon trading platform using sovereignty blockchain. In *2020 International Conference on Computer Engineering and Intelligent Control (ICCEIC)*, pages 149–152. IEEE.

Chakraborty, S., Anand, A., Kalash, D., and Srivastava, A. (2022). Transparency in carbon credit by automating data-management using blockchain. In *2022*

IEEE International Conference on Blockchain and Distributed Systems Security (ICBDS), pages 1–5. IEEE.

Chen, S. (2023). *Carbon Credit Markets*, pages 239–257. Springer.

Chicco, D., Warrens, M. J., and Jurman, G. (2021). The coefficient of determination r-squared is more informative than smape, mae, mape, mse and rmse in regression analysis evaluation. *Peerj computer science*, 7:e623.

Crosby, M., Pattanayak, P., Verma, S., and Kalyanaraman, V. (2016). Blockchain technology: Beyond bitcoin. *Applied Innovation*, 2(6-10):71.

Cui, S., Li, Y., and Chang, X. (2019). Research on model of blockchain-enabled power carbon emission trade considering credit scoring mechanism. *Electric Power Construction*, 40(2019):104–111.

Darby, M. and Gerretsen, I. (2019). Which countries have a net zero carbon goal. *Climate Change News. Available online at: https://www. climatechangenews. com/2019/06/14/countries-net-zero-climate-goal/(accessed July 29, 2019).*

Effah, D., Chunguang, B., Appiah, F., Agbley, B. L. Y., and Quayson, M. (2021). Carbon emission monitoring and credit trading: the blockchain and iot approach. In *2021 18th International Computer Conference on Wavelet Active Media Technology and Information Processing (ICCWAMTIP)*, pages 106–109. IEEE.

Francisco, L., Bonacin, R., and Rosa, F. D. F. (2022). A study on the application of blockchain in carbon trading systems. In *2022 IEEE/ACS 19th International Conference on Computer Systems and Applications (AICCSA)*, pages 1–6. IEEE.

Franke, L., Schletz, M., and Salomo, S. (2020). Designing a blockchain model for the paris agreement's carbon market mechanism. *Sustainability*, 12(3):1068.

Fu, B.-J., Su, C.-H., Wei, Y.-P., Willett, I. R., Lü, Y.-H., and Liu, G.-H. (2011). Double counting in ecosystem services valuation: causes and countermeasures. *Ecological research*, 26(1):1–14.

Giancaspro, M. (2017). Is a 'smart contract'really a smart idea? insights from a legal perspective. *Computer law & security review*, 33(6):825–835.

Golding, O., Yu, G., Lu, Q., and Xu, X. (2022). Carboncoin: Blockchain tokenization of carbon emissions with esg-based reputation. In *2022 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)*, pages 1–5. IEEE.

Hamet, P. and Tremblay, J. (2017). Artificial intelligence in medicine. *Metabolism*, 69:S36–S40.

Hartmann, S. and Thomas, S. (2020). Applying blockchain to the australian carbon market. *Economic Papers: A journal of applied economics and policy*, 39(2):133–151.

Hua, W. and Sun, H. (2019). A blockchain-based peer-to-peer trading scheme coupling energy and carbon markets. In *2019 international conference on smart energy systems and technologies (SEST)*, pages 1–6. IEEE.

Hyndman, R. J. and Koehler, A. B. (2006). Another look at measures of forecast accuracy. *International journal of forecasting*, 22(4):679–688.

Jani, S. (2017). An overview of ethereum & its comparison with bitcoin. *Int. J. Sci. Eng. Res*, 10(8):1–6.

Kenton, W. (2019). Carbon credit.

Kim, S.-K. and Huh, J.-H. (2020). Blockchain of carbon trading for un sustainable development goals. *Sustainability*, 12(10):4021.

Kirli, D., Couraud, B., Robu, V., Salgado-Bravo, M., Norbu, S., Andoni, M., Antonopoulos, I., Negrete-Pincetic, M., Flynn, D., and Kiprakis, A. (2022). Smart contracts in energy systems: A systematic review of fundamental approaches and implementations. *Renewable and Sustainable Energy Reviews*, 158:112013.

Kitchenham, B., Brereton, O. P., Budgen, D., Turner, M., Bailey, J., and Linkman, S. (2009). Systematic literature reviews in software engineering–a systematic literature review. *Information and software technology*, 51(1):7–15.

Li, G. and Li, J. (2021). Application and research of carbon asset management based on blockchain. In *Proceedings of the 2021 5th International Conference on Electronic Information Technology and Computer Engineering*, pages 672–679.

Liang, X., Du, Y., Wang, X., and Zeng, Y. (2019). Design of a double-blockchain structured carbon emission trading scheme with reputation. In *2019 34rd Youth Academic Annual Conference of Chinese Association of Automation (YAC)*, pages 464–467. IEEE.

Lin, K. Y. (2006). Dynamic pricing with real-time demand learning. *European Journal of Operational Research*, 174(1):522–538.

Lu, Y., Li, Y., Tang, X., Cai, B., Wang, H., Liu, L., Wan, S., and Yu, K. (2022). Stricts: A blockchain-enabled smart emission cap restrictive and carbon permit trading system. *Applied Energy*, 313:118787.

Mahesh, B. (2020). Machine learning algorithms-a review. *International Journal of Science and Research (IJSR).[Internet]*, 9(1):381–386.

Mandaroux, R., Dong, C., and Li, G. (2021). A european emissions trading system powered by distributed ledger technology: an evaluation framework. *Sustainability*, 13(4):2106.

Marchant, G. E., Cooper, Z., and Gough-Stone, P. J. (2022). Bringing technological transparency to tenebrous markets: The case for using blockchain to validate carbon credit trading markets. *Nat. Resources J.*, 62:159.

Mohanty, A. (2021). Impacts of climate change on human health and agriculture in recent years. In *2021 IEEE Region 10 Symposium (TENSYMP)*, pages 1–4. IEEE.

Muzumdar, A., Modi, C., and Vyjayanthi, C. (2022). A permissioned blockchain enabled trustworthy and incentivized emission trading system. *Journal of Cleaner Production*, 349:131274.

NB, S. S. (2023). Blockchain and iot-powered carbon credit exchange for achieving pollution reduction goals.

Patel, D., Britto, B., Sharma, S., Gaikwad, K., Dusing, Y., and Gupta, M. (2020). Carbon credits on blockchain. In *2020 International Conference on Innovative Trends in Information Technology (ICITIIT)*, pages 1–5. IEEE.

Peffers, K., Tuunanen, T., Rothenberger, M. A., and Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of management information systems*, 24(3):45–77.

Perdan, S. and Azapagic, A. (2011). Carbon trading: Current schemes and future developments. *Energy policy*, 39(10):6040–6054.

Rawat, V., Dahiya, N., Rai, S., and Arora, A. (2022). A blockchain-based decentralized framework for carbon accounting, trading and governance. In

Proceedings of the 2022 8th International Conference on Computer Technology Applications, pages 148–153.

Richardson, A. and Xu, J. (2020). Carbon trading with blockchain. In *Mathematical Research for Blockchain Economy: 2nd International Conference MARBLE 2020, Vilamoura, Portugal*, pages 105–124. Springer.

Sanner, M. F. (1999). Python: a programming language for software integration and development. *J Mol Graph Model*, 17(1):57–61.

Schneider, L. and La Hoz Theuer, S. (2019). Environmental integrity of international carbon market mechanisms under the paris agreement. *Climate Policy*, 19(3):386–400.

Shu, Z., Liu, W., Fu, B., Li, Z., and He, M. (2022). Blockchain-enhanced trading systems for construction industry to control carbon emissions. *Clean Technologies and Environmental Policy*, 24(6):1851–1870.

Sipthorpe, A., Brink, S., Van Leeuwen, T., and Staffell, I. (2022). Blockchain solutions for carbon markets are nearing maturity. *One Earth*, 5(7):779–791.

Spash, C. L. (2010). The brave new world of carbon trading. *New Political Economy*, 15(2):169–195.

Thirunavukkarasu, H., Rajendran, K., Dinesh, K., and Gunasekaran, S. (2023). Application of blockchain and iot in cap and trade of carbon emissions. In *2023 International Conference on Recent Advances in Electrical, Electronics, Ubiquitous Communication, and Computational Intelligence (RAEEUCCI)*, pages 1–5. IEEE.

Tuerk, A. and Zelljadt, E. (2016). The global rise of emissions trading — climate policy info hub.

Vilkov, A. and Tian, G. (2023). Blockchain's scope and purpose in carbon markets: A systematic literature review. *Sustainability*, 15(11):8495.

Wang, M., Wang, B., and Abareshi, A. (2020). Blockchain technology and its role in enhancing supply chain integration capability and reducing carbon emission: A conceptual framework. *Sustainability*, 12(24):10550.

Wang, X., Du, Y., and Liang, X. (2019). A reputation-based carbon emissions trading scheme enabled by block chain. In *2019 34rd Youth Academic Annual Conference of Chinese Association of Automation (YAC)*, pages 446–450. IEEE.

Wara, M. and Victor, D. G. (2008). A realistic policy on international carbon offsets. *Program on Energy and Sustainable Development Working Paper*, 74:1–24.

Woo, J., Fatima, R., Kibert, C. J., Newman, R. E., Tian, Y., and Srinivasan, R. S. (2021). Applying blockchain technology for building energy performance measurement, reporting, and verification (mrv) and the carbon credit market: A review of the literature. *Building and Environment*, 205:108199.

Yuan, L., Dong, J., Wang, N., Chen, Z., and Gong, G. (2021). Blockchain-based carbon allowance trading market construction. In *2021 IEEE Sustainable Power and Energy Conference (iSPEC)*, pages 245–248. IEEE.

Zhang, T.-y., Feng, T.-t., and Cui, M.-l. (2023). Smart contract design and process optimization of carbon trading based on blockchain: The case of china's electric power sector. *Journal of Cleaner Production*, 397:136509.

Zhao, N., Sheng, Z., and Yan, H. (2021). Emission trading innovation mechanism based on blockchain. *Chinese Journal of Population, Resources and Environment*, 19(4):369–376.

Zhou, Q. and Zhang, Q. (2022). Simulation research on carbon emissions trading based on blockchain. *Journal of Environmental Engineering and Landscape Management*, 30(1):1–12.