



Mudala: A Blockchain-based Carbon Credit Exchange Platform

by

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Declaration

I, Liso Nyandu, declare that this thesis is composed of my original work, it contains no material previously published or written by another person except where due reference has been made in the text. This thesis is submitted to the University of Cape Town for the Master of Philosophy in Financial Technology degree.

October 31, 2024

Signed by candidate

Signature

Date

Abstract

Climate change is one of the most pressing issues of our time, with constantly increasing greenhouse gas (GHG) emissions posing a severe threat to our planet. Businesses must adopt net-zero strategies such as reducing energy use, adopting carbon-neutral technologies, and trading on carbon markets to mitigate the effects of climate change. However, existing carbon markets, which are meant to incentivise emission reduction, face critical challenges such as a lack of trust and transparency, over-crediting, and high trading costs, hindering their effectiveness.

We propose Mudala - a proof-of-concept carbon exchange built on the Algorand blockchain - to overcome these challenges. By leveraging blockchain technology's decentralised, immutable, and peer-to-peer transacting properties, Mudala enables firms to list carbon-offsetting projects, which, once approved by a regulator, are available for purchase as carbon credits by firms seeking to offset their emissions. The carbon credits exist as fungible tokens on a secure distributed ledger. Each firm authenticates using its unique Algorand account to access the web-based carbon exchange. The Paris Agreement highlights the urgent need for secure digital infrastructure to ensure data integrity and accurate emission tracking. The design of Mudala is undertaken within this context, and the resulting proof-of-concept demonstrates such secure digital infrastructure, which enhances trust, transparency, efficiency, and accessibility in carbon markets.

To assess Mudala's effectiveness in addressing climate challenges, we employ a blockchain suitability workflow based on technical performance, data governance and access criteria. This analysis confirms the suitability of enabling Mudala's marketplace capability using blockchain. Our proof-of-concept successfully showcases secure digital infrastructure in carbon markets, aligned with the Paris Agreement's goals for data integrity and accurate emission tracking. While Mudala's features are promising, real-world data on user engagement, project participation, and user feedback are crucial to fully validate its effectiveness and scalability.

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Abbreviations and Acronyms

UNFCCC	UN Framework Convention on Climate Change
GHG	Greenhouse Gas (or Greenhouse Gases)
JI	Joint Implementation
CDM	Clean Development Mechanism
ETS	Emissions Trading Scheme
AMM	Automated Market Makers
EU	European Union
PoW	Proof of Work
PoS	Proof of Stake
CO	Carbon dioxide
NDC	Nationally Determined Contributions
CCM	Compliance Carbon Markets
VCM	Voluntary Carbon Market
GS	Gold Standard
VCS	Verified Carbon Standard
CCS	Credible Carbon Standard
IPCC	Intergovernmental Panel on Climate Change
SDG	Sustainable Development Goals

1. Introduction

1.1 Background and Context of the Study

The 21st century faces a significant challenge, with escalating GHG emissions driving climate change and global warming. These changes have resulted in devastating consequences, including unprecedented floods, heatwaves, and wildfires. The atmosphere and oceans have warmed, leading to rising sea levels and a substantial decline in Arctic sea ice (IPCC 2021). Even plants and animals struggle to keep up as their habitats change rapidly. Fossil fuel burning, a result of human activities since the Industrial Revolution, has led to a substantial increase of over 40% in atmospheric CO₂ concentrations (Royal Society and National Academy of Sciences 2020). This rise in greenhouse gases directly impacts global temperatures. According to NASA Earth Observatory (2023), the past nine years have been the warmest on record, and Earth is now averaging 1.11°C hotter than the late 19th century. This warming trend represents a significant acceleration, with global temperatures increasing by an average of 0.15 to 0.20°C per decade since 1975.

The United Nations established the Sustainable Development Goals (SDGs) in 2015, driven by the need to address global challenges. Among them, SDG 13¹, which focuses on urgent action to combat climate change and its impacts, is a crucial pillar in this global effort. In light of this, as 2030 approaches, businesses face increasing pressure to adopt net-zero strategies, reducing energy consumption and transitioning to carbon-neutral technologies. However, a critical gap remains: How do we incentivise emissions reductions beyond existing measures? Carbon markets come in at this point. These platforms offer a market-based solution where the trading of carbon credits, each representing one tonne of CO₂ equivalents (CO₂e) reductions, takes place. Carbon markets hold significant potential by providing a financial incentive for emissions reduction and channelling resources towards sustainable practices. Approximately 40 countries and 20 cities/states/provinces have embraced carbon pricing mechanisms, covering about 13% of annual global emissions (World Bank Group 2018). International collaboration is key

¹SDG 13: <https://www.globalgoals.org/goals/13-climate-action/>

in addressing this global challenge. The Kyoto Protocol² and the Paris Agreement³ are testaments to this commitment, encouraging countries to set emissions reduction targets. Article 6 of the Paris Agreement further paves the way for cooperative approaches, allowing diverse emissions reductions (often represented as carbon credits) achieved through various climate actions (such as afforestation and renewable energy projects) to be traded and transferred between participating countries. The EU Emissions Trading System (ETS), a cap-and-trade system limiting emissions from power plants, industrial facilities, and airlines within the EU, and other regional initiatives are examples of collaborative efforts currently in progress (World Bank Group 2018). Carbon reduction is even more critical for developing countries like South Africa. While vulnerable to climate change due to its developing status, the government actively pursues a low-carbon future. As a member of the UN Framework Convention on Climate Change (UNFCCC), it actively supports global efforts to stabilise greenhouse gas concentrations by contributing to international agreements and participating in climate negotiations. Policymakers established the National Climate Change Response Policy (NCCRP) and National Development Plan (NDP) in 2011 to integrate climate considerations into development policies and plans and enable effective monitoring and reporting of GHG emissions, mitigation efforts, and adaptation actions.

Between 2013 and 2015, Promethium Carbon⁴ explored the viability of carbon trading in South Africa, concluding that the necessary infrastructure and potential supply and demand exist for a carbon offset trading scheme alongside the already implemented carbon tax (Department of Energy - RSA 2016). However, introduced in 2019, South Africa's initial carbon tax price of R120 (\$7) per ton of CO₂ equivalent exhibited limited effectiveness due to its relatively low cost compared to major export markets (Deidda et al. 2022). As of 2023, research on a South African carbon offset trading scheme remains limited, offering further development and implementation opportunities.

Beyond South Africa, carbon markets like the EU ETS face challenges such as a lack of transparency, over-crediting, and high transaction costs (Braden 2019; Saraji and Borowczak 2021). Their centralised nature and reliance on separate registries further contribute to these issues. With its decentralised transactions and immutability, blockchain technology presents a potential solution to these challenges. It ensures data integrity and security, and its distributed ledger fosters transparency, making it well-suited for carbon market needs (World Bank Group 2018).

These blockchain features lead us to this study's central question: Can blockchain address the challenges facing existing carbon markets and enhance our fight against

²The Kyoto Protocol: https://unfccc.int/kyoto_protocol

³The Paris Agreement: <https://unfccc.int/process-and-meetings/the-paris-agreement>

⁴Promethium Carbon: <https://www.promethium.co.za/>

climate change? In this study, we present Mudala, a proof-of-concept carbon trading enabled by blockchain technology. Mudala utilises fungible tokens to represent carbon credits, facilitating a more transparent, efficient, and accessible trading environment for businesses seeking to offset their emissions. By exploring Mudala's capabilities, we hope to pave the way for a future where innovative technology empowers us to combat climate change and build a more sustainable world.

1.2 Research Questions and Objectives

1.2.1 Research Questions

This study focuses on this central research question:

Main Question:

RQ1: Can blockchain technology address the limitations of existing carbon markets, thereby enhancing transparency, reducing over-crediting, and lowering transaction costs?

Sub-Questions:

We further break down the central question into the following sub-questions:

RQ2: How can a decentralised carbon credits marketplace enabled by blockchain technology increase accessibility and efficiency in carbon trading among businesses in developing countries like South Africa, mainly inline with SDG 13's objectives?

RQ3: How do specific features of the blockchain technology, such as immutability and decentralisation, contribute to Mudala's effectiveness in promoting international collaboration, transparency, and emissions reduction efforts aligned with the Paris Agreement's goals of facilitating transparent and efficient global emissions reduction, technology transfer, and financial support for developing nations?

1.2.2 Research Objectives

This research seeks to accomplish the following objectives:

Obj.1: Develop and implement a proof-of-concept decentralised carbon credits marketplace, Mudala, using blockchain technology to address the limitations of existing centralised systems regarding transparency, over-crediting, and high transaction costs.

Obj.2: Evaluate the effectiveness of Mudala in terms of transparency, efficiency, accessibility, and potential contribution to carbon emissions reduction, both within South Africa and globally, considering its alignment with the Paris Agreement's goals and specific targets related to SDG 13.

Obj.3: Analyse the specific features of the blockchain technology employed in Mudala and assess their contribution to the platform's functionality, particularly its ability to foster international collaboration in carbon mitigation strategies aligned with the Paris Agreement's goals of facilitating transparency, technology transfer, and financial support for developing nations.

1.3 Methodology

1.3.1 Research Design and Approach

This research uses a mixed-methods approach, combining exploration and description (Saunders et al. 2016). Similar to research questions, projects can have multiple purposes. This research explores carbon markets and their unique challenges, aiming to gain new insights and understand the landscape in a fresh light (Saunders et al. 2016). This aligns with our goal of comprehensively understanding the existing carbon market landscape and its limitations. Additionally, as Saunders et al. (2016) described, the descriptive component aims to create an accurate profile of the Mudala platform and its potential impact on the South African carbon market. This will be achieved by evaluating Mudala's effectiveness in achieving transparency, efficiency, accessibility, and carbon emissions reduction.

1.3.2 Data Sources and Collection

The research primarily relies on document analysis, supported by data gathered through:

- 1. Systematic Literature Review:** Encompasses peer-reviewed and grey literature on carbon markets, blockchain applications, and relevant SDGs. This aids in understanding existing challenges and potential solutions.

- 2. Key Policy Documents Informing Mudala Development:** Carbon Offset Paper (National Treasury 2014). Provides details about the proposed carbon offset scheme in South Africa, complementing the Carbon Tax Policy Paper.

South Africa's Carbon Offsets Administrative and Reporting System: Synthesis Report (Department of Energy - RSA 2016). Analyses international best practices and the existing South African system to inform the development of the country's carbon offset scheme.

1.3.3 Data Analysis Techniques

This research employs thematic analysis, a qualitative method for identifying and interpreting recurring patterns or themes within data (Maguire and Delahunt 2017). This approach aligns with the exploratory and descriptive elements of our research design, allowing us to:

- 1. Uncover critical themes and trends:** By systematically examining the findings from the systematic literature review, we aim to identify recurring topics, challenges, and potential solutions related to carbon markets and blockchain applications. This

will provide a comprehensive understanding of the current landscape and inform the development of Mudala.

2. Extract meaningful insights: By analysing research and discussions on blockchain in carbon markets, the analysis will aim to identify critical areas where this technology can contribute to improvements.

1.3.3.1 Evaluation Framework

The evaluation of Mudala's effectiveness leverages a framework adapted from (Schletz et al. 2020), incorporating the following classifiers:

1. Overall Blockchain Applicability: Assesses whether blockchain is generally suitable for the carbon credit marketplace.

2. Distributed Ledger Technology (DLT) Type: Determines if blockchain or another DLT is more appropriate.

3. Blockchain Permission Level: Evaluates the need for a public, private, or consortium blockchain.

4. Scalability and Performance: Considers transaction throughput and latency requirements.

5. Security and Privacy: Assesses security mechanisms and data privacy needs.

6. Interoperability and Integration: Evaluates the ability to connect with existing systems and platforms.

7. Governance and Consensus Mechanisms: Determines the most suitable governance and consensus mechanisms.

8. Data Accessibility and Transparency: Assesses data accessibility and transparency requirements.

1.4 Research Outcomes

This research has two primary outcomes:

1. Blockchain Suitability Criteria for Carbon Markets: This research identifies and evaluates key criteria for determining the suitability of blockchain technology for carbon credit marketplaces, specifically within the South African context. These criteria encompass technological and governance considerations, providing a valuable framework for future implementation.

2. Mudala: A Proof-of-Concept Blockchain-Based Carbon Trading Platform: Mudala serves as a demonstration of the feasibility and potential benefits of blockchain technology in carbon trading. Key features facilitated by Mudala include:

Carbon credit issuance and validation by regulators: Ensures compliance with standards and regulations.

Carbon credit requests by sellers: Enables verified offset projects to offer carbon credits as fungible tokens on the blockchain.

Carbon credit purchases by buyers: Allows buyers to purchase carbon credits (as fungible tokens) to offset their CO₂ emissions.

1.5 Key Definitions

The key concepts for this study are defined below:

Blockchain - A distributed, immutable ledger where transactions are grouped into blocks. Blocks are cryptographically linked, forming a secure, verifiable history of data (Zheng et al. 2017).

Tokenisation - The process of representing real-world assets (like property, currency, or carbon credits) as digital tokens on a blockchain (Hileman and Rauchs 2017).

Decentralised Application (DApp) - An application built on a blockchain network that operates independently of centralised control. Its backend code runs on a distributed peer-to-peer network (Zheng et al. 2021).

Proof of Stake (PoS) - A blockchain consensus mechanism where validators stake their cryptocurrency to participate in transaction and block validation. The chance of being selected as a validator increases with the amount staked (Zheng et al. 2017).

Proof of Work (PoW) - A blockchain consensus mechanism where nodes (miners) compete to solve complex mathematical puzzles to validate blocks and earn rewards. PoW is computationally intensive and consumes significant energy (Nakamoto 2008).

Carbon Credit - A tradable permit representing the removal or reduction of one metric ton of carbon dioxide equivalent (CO₂e) emissions (Saraji and Borowczak 2021).

Greenhouse Gas (GHG) - Any gas in the atmosphere that absorbs and emits infrared radiation, contributing to the greenhouse effect and climate change. Examples include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) (Jeffry et al. 2021).

Article 6.2 - A provision within the Paris Agreement that allows countries to cooperate in achieving their emissions reduction targets (NDCs) through mechanisms like international carbon markets (Streck, Keenlyside, and Von Unger 2016).

Carbon Offset Credit - A tradable certificate representing the verified reduction, avoidance, or removal of one metric ton of CO₂e emissions. Offset credits can be used to compensate for an individual's or organisation's carbon footprint (Broekhoff et al. 2019).

Carbon Standard - A set of criteria and procedures for the development and certification of carbon offset projects. Standards ensure that offset credits represent genuine and verifiable emissions reductions.

Kyoto Protocol - An international treaty adopted in 1997 that aimed to reduce greenhouse gas emissions by developed countries. It established early forms of carbon markets.

Paris Agreement - An international agreement adopted in 2015 with the goal of limiting global warming to well below 2°C, preferably 1.5°C, compared to pre-industrial levels. It includes provisions for carbon markets and international cooperation.

Sustainable Development Goals (SDGs) - A collection of 17 global goals set by the United Nations to address social, economic, and environmental challenges by 2030. Climate action (SDG 13) is a key focus.

EU Emissions Trading Scheme (EU ETS) - The world's first and largest cap-and-trade system for carbon emissions. It covers power plants, industrial installations, and aviation within the European Union.

1.6 Thesis Outline

The remainder of this thesis is organised as follows:

Chapter 2 - A review of literature on different types of carbon markets, carbon pricing, problems with existing markets, potential carbon credit demand and supply, carbon standards, and blockchain features and benefits.

Chapter 3 — Design of Mudala - a decentralised carbon credit marketplace.

Chapter 4 — Implementation of Mudala.

Chapter 5 — Evaluation of Mudala.

Chapter 6 — Conclusion and recommendations for future research.

2. Literature Review

2.1 A Brief History of Carbon Markets

Emissions trading emerged in the 1960s as a market-based solution to air pollution, granting companies the right to buy and sell pollution permits (Calel 2011). This market-based approach incentivised emission reductions, as companies with excess permits could profit by selling them to those in need. The concept gained traction in the 1990s, driven by the potential for market mechanisms in mitigating GHG emissions. Article 4.2 of the UNFCCC played a crucial role in this development, facilitating pilot projects like those in the US and Costa Rica (Michaelowa et al. 2019). These projects paved the way for broader market mechanisms under the UNFCCC and Kyoto Protocol. Since then, numerous countries and regions have embraced cap-and-trade systems, carbon taxes, and other market-based tools to tackle GHG emissions. Michaelowa et al. (2019) identify four distinct phases in this evolution: During the Emergence phase (1997-2004), the Clean Development Mechanism (CDM) and Joint Implementation (JI) were operationalised, requiring standardised baselines and monitoring procedures.

The Gold Rush phase (2005-2011) saw rapid market expansion fuelled by the EU ETS linking directive. The Fragmentation phase witnessed a decline in carbon prices, limiting new project development. This decline was driven by both domestic quantitative limits on offset use imposed by the EU ETS and international uncertainties surrounding the second Kyoto Commitment Period. The current phase, Post-Paris Perspectives (from 2015), has significantly changed the international climate regime. Global participation has replaced the Kyoto focus on developed countries, but complexity has increased. Voluntary mitigation targets are set through Nationally Determined Contributions (NDCs) instead of strict "carbon budgets." Although Article 6 mentions future market mechanisms, details and effectiveness must be clarified.

The figure below depicts the dynamic journey of international carbon markets, highlighting four distinct periods marked by specific challenges and regulatory frameworks.

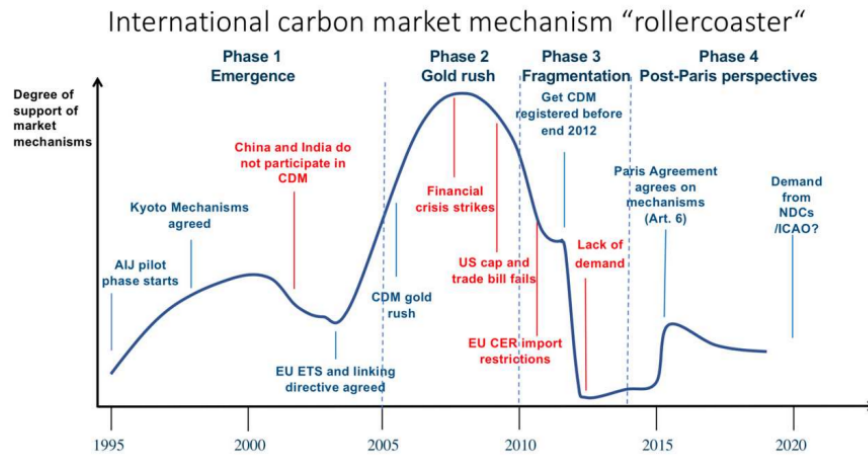


Figure 2.1: Evolution of International Carbon Markets: Phases, Challenges, and Drivers.

(Source: Michaelowa et al. 2019)

2.2 Types of Carbon Markets

Over 60 emissions-trading systems and carbon taxes are operational or planned globally, covering roughly one-fifth of greenhouse gas emissions (Sipthorpe et al. 2022). Compliance carbon markets (CCMs), like the EU ETS – the world’s largest, covering 45% of EU emissions and achieving a 20% reduction by 2020 compared to 1990 levels – play a key role. These regional or national markets regulate and trade allowances to emit carbon, incentivising companies to reduce their footprint. In contrast, voluntary carbon markets (VCMs) provide alternative pathways for emissions mitigation. Fuelled by net-zero ambitions, companies and individuals can trade carbon credits generated by emission reduction projects (UNEP 2021). While smaller than CCMs, VCMs have seen a 100-fold increase in demand for offsets this past decade (Hamrick and Gallant 2018). Beyond CCMs and VCMs, noteworthy initiatives include Article 6 of the Paris Agreement, fostering international cooperation for nationally determined contributions, and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aiming for carbon-neutral aviation growth (Stua et al. 2022).

2.2.1 Compliance Carbon Markets (CCMs)

2.2.1.1 Emission Trading Systems (Cap-and-Trade System)

Emission trading systems are a core tool within CCMs. An ETS works by setting a cap (limit) on total allowable emissions. Companies within the system receive or buy permits (allowances), each allowing them to emit a specific amount of greenhouse

gases (Egenhofer et al. 2006). By controlling the number of permits, the system creates scarcity and drives efficiency. Companies emitting less than their allocation can sell surplus allowances to higher emitters, creating a dynamic carbon market. For example, EU ETS covers the 12,000 largest emitters across the EU and neighbouring countries. Power stations and manufacturers receive allowances through auctions, setting the carbon price. Companies can freely trade these allowances and must report their emissions, surrendering enough allowances to cover the previous year or face fines.

2.2.1.2 Carbon Taxes

Carbon taxes are a direct approach to tackling global warming by making carbon emissions more expensive for businesses and individuals (Hu et al. 2020). This directly incentivises emissions reduction by raising the cost of producing and consuming carbon-intensive goods and services (Chai et al. 2018). Carbon taxes can be structured in various ways, targeting either direct emissions or the carbon content of fuels. The tax rate is usually based on one of these metrics, aiming to discourage activities with high carbon footprints. Governments implement carbon taxes by setting a fixed price per unit of carbon emissions (e.g., per ton of CO₂). This creates a market-based incentive for businesses to reduce their emissions and potentially raises revenue for climate-related initiatives (Stavins 2019). Designing an effective carbon tax requires careful consideration of several key factors, such as the tax base, rate, revenue allocation, and consumer impact. The tax base identifies which emissions or fuel sources will be taxed. The tax rate must be high enough to incentivise companies to reduce their emissions but not so high that it cripples economic activity. Revenue allocation must be fair and effective, and the tax should be designed to minimise the impact on consumers. While frequently applied to fuels like gasoline, coal, and natural gas, specific industries may be exempt or subject to lower rates, depending on policy design (Sumner et al. 2011).

2.2.2 Voluntary Carbon Markets

Voluntary carbon markets capitalise on the willingness of entities to offset their emissions beyond regulatory requirements (Sipthorpe et al. 2022). They can complement CCMs by funding projects ineligible for compliance markets (Hamrick and Gallant 2018). Unlike CCMs, offsets in VCMs are not determined by cap-and-trade, but by standardised rules developed by independent verifiers like The Gold Standard and Voluntary Carbon Standard (Sipthorpe et al. 2022). This certification ensures the credibility of purchased offsets. VCMs offer lower administrative burdens, attracting smaller project owners who might struggle with high UN certification costs (Kollmuss et al. 2008). The lack of

stringent regulations also fosters flexibility in project design, encouraging innovation and experimentation. This empowers small communities in developing countries to participate in carbon markets, even with projects too small for CCMs. Successful technologies tested in these smaller projects can be scaled up and integrated into regulated markets later on (Kollmuss et al. 2008).

2.3 Carbon Pricing: A Global Snapshot of Benefits and Implementation

Carbon pricing, through cap-and-trade systems or taxes, aims to reduce greenhouse gas emissions by commonly expressing the cost of carbon. Prices are typically measured in US dollars per metric ton of carbon dioxide (\$/mt CO₂), providing a standardised unit for comparison. For instance, a \$1/mt CO₂ price equals roughly \$0.43 per barrel of oil, \$0.01 per gallon of gasoline, and €0.003 per litre of petrol (Boyce 2018). This approach generates several benefits, making it an increasingly popular policy tool worldwide.

2.3.1 Benefits of Carbon Pricing

1. Incentivised emission reductions: By making carbon-intensive activities more expensive, businesses and individuals are encouraged to adopt cleaner technologies and practices, leading to cost-effective relative emission reductions (Thube et al. 2021). This incentivises the transition towards low-carbon alternatives like LED lighting or wind power, ultimately decreasing overall emissions (Boyce 2018).

2. Revenue generation: Carbon pricing generates substantial funds through taxes and auction revenues (Marten and Van Dender 2019). These resources can be allocated towards climate mitigation efforts, adaptation projects, and social programs to address potential distributional impacts associated with the transition to a low-carbon economy (Boyce 2018). Studies show that effective carbon rates can generate over 1% of GDP in many OECD and G20 countries, potentially doubling if aligned with ambitious climate goals (Marten and Van Dender 2019). Additionally, these funds can be used to invest in research and development of clean technologies.

3. Innovation in clean technologies: Innovation in clean technologies: Rising carbon prices create a long-term incentive for research and development in clean technologies (Boyce 2018). As the cost of emitting carbon increases, the pressure to find cheaper alternatives stimulates breakthroughs in areas like renewable energy and carbon capture, ultimately driving down the cost of future emission reductions. Past examples

like the US sulphur dioxide cap-and-trade program demonstrate the potential for carbon pricing to spur innovation in clean technologies (Boyce 2018).

2.3.2 Global Snapshot of Carbon Pricing

Table 2.1: Global Overview of Carbon Pricing Mechanisms

Region	Country	Mechanism Type	Coverage (%)	Price (USD/t CO ₂ e)
Africa	South Africa	Carbon Tax	90%	\$8.45
	Nigeria	Considering ETS	N/A	N/A
Asia	China	ETS	46%	\$8
	South Korea	ETS	74%	\$17
	Japan	ETS	75%	\$3
	Kazakhstan	ETS	43%	\$1
	Others (Indonesia, etc.)	Considering Mechanisms	N/A	N/A
Europe	European Union	EU ETS	39%	\$50
	Germany	ETS	N/A	\$29
	Poland	Carbon Tax	0.04%	\$0.08
	Others (Austria, Sweden, etc.)	Various Taxes/ETS	Varies	Varies
North America	Canada	Hybrid (ETS and Tax)	ETS: 9%, Tax: 22%	\$50
	USA (States)	State ETS	N/A	N/A
Oceania	New Zealand	ETS	51%	\$76
South America	Mexico	Carbon Tax	23%	\$3
	Mexico	Planned ETS	40%	N/A
	Colombia, Argentina	Carbon Tax	N/A	N/A
	Chile	Exploring Options	N/A	N/A

As shown in Table 2.1, various regions worldwide have implemented diverse carbon pricing mechanisms, including carbon taxes and emissions trading systems (ETS), with varying coverage and price levels. These mechanisms reflect each region's approach to mitigating greenhouse gas emissions, influenced by economic, political, and environmental factors. Africa, for instance, sees South Africa leading with a carbon tax covering 90% of emissions, while other African nations are considering similar policies. Asia exhibits a mix of established ETSs and countries exploring new mechanisms. Europe's comprehensive adoption of carbon pricing, particularly the EU ETS, demonstrates a strong commitment to emission reductions. North America's approach varies between federal and state levels, and Oceania and South America are progressively enhancing their carbon pricing strategies. For more detailed information on country-specific ETS systems, please refer to Appendix A.1.

2.4 South African Carbon Market

2.4.1 Vision and Policy Framework

South Africa's commitment to a low-carbon future began in 2011 with the National Climate Change Response White Paper, setting the stage for a climate-resilient economy. The 2013 Carbon Tax Policy Paper further solidified this commitment by outlining a tax to incentivise cleaner investments through increased emission costs for businesses (National Treasury 2014). This policy was complemented by the 2014 carbon offset paper, proposing both international and domestic offset markets to enhance flexibility and cost-effectiveness (National Treasury 2014). However, the oligopolistic nature of the energy market led to the exclusion of electricity generators from initial trading (Lozynskyy et al. 2014).

Challenges and Key Emitters: Identifying significant contributors to South Africa's industrial emissions was crucial for targeted mitigation strategies. Lozynskyy et al. (2014) highlighted iron and steel, ferroalloys, cement, and other energy-intensive industries as critical targets. Meanwhile, the (Department of Environmental Affairs 2016) emphasised the need for accurate emission estimates, particularly from the dominant electricity generation sector. Arp, Upadhyaya, and Naudé (2018) further explored the potential and challenges of carbon trading in South Africa, emphasising the need for a voluntary, sustainable, and transparent system aligned with the Paris Agreement (2015).

Carbon Tax Implementation and Progress: A significant step towards emission reduction came in June 2019 with the introduction of carbon tax legislation (IFM 2023). It aims to achieve a 42% reduction below "business as usual" emissions by 2025, aligning with South Africa's Paris Agreement commitments. The tax began at R120 per ton of CO₂e (\$7) in 2019 and increased to R159 (\$8.5) by 2023 (KPMG 2023). Statista (2023) states that South Africa generated 405 Mt CO₂ in 2022, a 3% decrease from 2021. Despite this, South Africa's reliance on coal keeps it among the top 15 global emitters. The country's updated NDCs commit to reducing GHG emissions to 350-420 Mt CO₂e by 2030 and achieving carbon neutrality by mid-century (United Nations Development Programme 2023). Achieving these goals requires developing effective climate policies, including Phase 2 of the carbon tax. This phase targets a significantly higher price range of US\$50-100/t CO₂e by 2030, aiming to drive both emission reductions and technological advancements. Precise policy trajectories and regular monitoring will be crucial to ensure its effectiveness.

2.5 Carbon Offset Standards

A carbon offset credit is a verifiable certificate representing the reduction or removal of one metric ton of CO₂ equivalent (CO₂e) greenhouse gases. Different offset standards exist to ensure quality (National Treasury 2014). Clean Development Mechanism (CDM)¹ is a dominant standard in global markets. Verified Carbon Standard (VCS)² is the most widely used voluntary offset standard. Gold Standard (GS)³ focuses on renewable energy and efficiency projects. Meanwhile, the Climate, Community & Biodiversity Standard (CCBS)⁴ emphasizes land management projects with broader benefits. Numerous regional carbon offset standards exist alongside global standards. Driven by governments, they align with unique local conditions and climate goals (Department of Energy - RSA 2016). Examples include California and RGGI Offset Schemes (US), Australia's Carbon Farming Initiative, Japan's J-VER, and more. Regional standards are often tied to mandatory offset programs, directly supporting national climate targets. South Africa has its own, the Credible Carbon Standard (CCS), designed to promote domestic, smaller-scale projects focusing on renewable energy and emission reduction initiatives.

2.6 Potential Carbon Credits Demand

The global carbon market is booming, with a total trading value of \$865 billion in compliance markets and \$2 billion in voluntary markets in 2022 (CAP-A 2023). Both sectors have doubled since 2020, and the voluntary market is projected to reach \$10-40 billion by 2030 (CAP-A 2023). While Africa currently holds only 11% of the market share, its growth rate surpasses the global average, driven by major international companies seeking African carbon credits. The demand for voluntary carbon markets is expected to grow 15 times by 2030 due to increasing corporate net-zero commitments and the availability of point-of-sale offsetting.

However, predicting the future demand for carbon offsets in South Africa is challenging due to the underdeveloped nature of the market. The National Treasury (2014) reports that four independent studies have attempted to estimate demand under a carbon tax scenario, each using different data and assumptions: Camco Clean Energy (2012), Promethium Carbon (2012 and 2014), and C4 EcoSolutions (2013). Camco

¹Clean Development Mechanism: <https://cdm.unfccc.int/>

²Verified Carbon Standard: <https://verra.org/project/vcs-program/>

³Gold Standard: <https://www.goldstandard.org/>

⁴Climate, Community & Biodiversity Standard: <https://verra.org/project/ccb-program/>

Clean Energy's study used data from the Second National Communication under the UN Framework Convention on Climate Change, estimating a national demand of 25-30 million tonnes CO₂e per year with maximum offset purchase. Meanwhile, Promethium Carbon (2012) utilised data from the Long Term Mitigation Scenarios report. It estimated an annual demand of around 30 million tonnes, assuming that the tax covers half of the country's emissions. Promethium Carbon (2014) combined IPCC emission factors, energy demand projections, and process emissions projections to develop a low-end demand of 5-8 million tonnes and a high-end demand of 18-20 million tonnes per year.

2.7 Carbon Credits Supply

Africa has a shallow participation rate in carbon markets, with only 11% of all retired credits in the Verified Carbon Standard coming from Africa between 2016 and 2021. The continent has few project developers who are relatively small-scale and show limited diversification. There are around 100 project developers in Africa, with only 15 issuing around 70% of total credits (ACMI 2022). Moreover, most of these developers have operated in only one country, and over 60% have operated just one project. Achieving the 300 Mt CO₂e retirement target by 2030 could require 100 project developers to issue several credits yearly (2 times the number of issuers in 2021). The National Treasury (2014) provides an overview of various studies estimating the potential supply of carbon offsets in South Africa. These studies, employing diverse methodologies, include Camco Clean Energy (2012), IGES (2012), UNEP Risoe (2012), and Promethium Carbon (2012). The studies suggest that the potential supply could range from 20 to 29 million tonnes annually by 2030, with CDM projects contributing around 17.2 million tonnes annually. Other potential contributors include projects outside the carbon tax net (4.5 to 8.6 million tonnes per year), residential projects (5 to 11.5 million tonnes per year), the REIPP program (4.4 to 4.9 million tonnes per year), and existing carbon credit projects (4 million tonnes per year). Carbon sequestration and emissions reduction in South Africa have the potential to supply at least 54.8 million t CO₂e per year. However, the actual supply will depend on various factors such as project development costs, carbon prices, and policy incentives.

2.8 Problems with Existing Cap-and-Trade System

Current carbon trading systems face several challenges that make it difficult to reduce climate change effectively. These problems arise due to the emergence of diverse global and regional credits, markets, and trading mechanisms, leading to a lack of coordination

and communication among them (Saraji and Borowczak 2021). This section will explore critical issues within these systems and their implications.

2.8.1 Over - Crediting

Over-crediting occurs when baseline emissions are miscalculated, or project reductions are overestimated, leading to an oversupply of credits with declining value (Schneider et al. 2015). This discourages genuine emissions reductions and misdirects climate mitigation funds to less impactful projects (Saraji and Borowczak 2021; Haya et al. 2023). Project-based mechanisms are particularly vulnerable due to information asymmetry between project developers and auditors (Cames et al. 2016; Haya et al. 2010; Schneider et al. 2015).

2.8.2 Unclear Life Cycle and Validity of Carbon Credits

Issued credits' unclear origin and verification processes raise concerns about their legitimacy and hinder market transparency (Saraji and Borowczak 2021). This lack of trust weakens the system's effectiveness and allows projects with questionable quality to benefit from lower offset prices, further hindering efficient mitigation efforts (Haya et al. 2023).

2.8.3 Double Spending

Double counting the same emission reduction multiple times towards mitigation targets is a significant challenge in reducing greenhouse gases (Schletz et al. 2020). It can occur through double issuance (issuing multiple units for the same emission reduction), double claiming (counting reductions twice), or double use (using the same unit twice) (Sipthorpe et al. 2022). Lack of transparency and communication between regions and markets makes it difficult to ensure that credits are sold only once and emissions are genuinely reduced (Saraji and Borowczak 2021).

2.8.4 High Transaction Costs and Wealth Concentration

High transaction costs plague current carbon trading markets, primarily benefiting brokers and agents (Saraji and Borowczak 2021). Traders and brokers often receive significant commissions (3-8% of credit value) (Sovacool 2011). This discourages smaller companies' participation and concentrates wealth in the hands of intermediaries.

2.8.5 Conflict of Interest with Third-Party Verifiers

Third-party verifiers assess project developers' claims in existing carbon trading systems (Saraji and Borowczak 2021). However, a conflict of interest and potential moral hazard arises as these verifiers are often paid directly by the project developers themselves (Sovacool 2011). This incentivises verifiers to approve all projects they investigate, compromising the verification process's impartiality and credibility.

2.9 Blockchain Technology and its Features

Blockchain is a public ledger where transactions are stored in blocks, which are appended to prior blocks, creating a growing chain of records (Zheng et al. 2017). An illustration of this process can be found in Figure 1, as described in Nakamoto (2008)'s white paper that introduced Bitcoin.

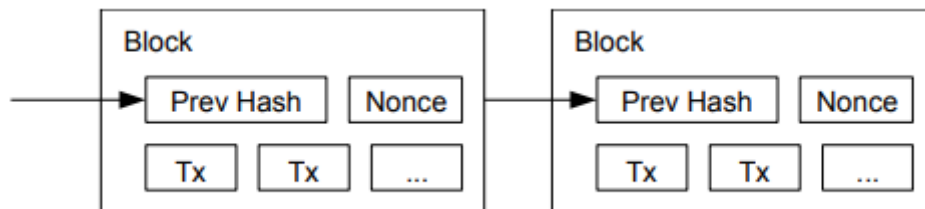


Figure 2.2: An illustration by Nakamoto (2008) of how blockchain works.

Each transaction on the blockchain is agreed upon through a consensus mechanism by the majority of participants in the network. Nodes use a protocol known as a consensus mechanism to ensure agreement on which transactions are added to the ledger. In a centralised system, decisions can be made by a central node, but in a decentralised system, this consensus mechanism is necessary to maintain consistent recording of transactions (Zheng et al. 2017).

Various consensus mechanisms exist, with Bitcoin currently using Proof-of-Work, while Ethereum recently shifted to a Proof-of-Stake protocol (Kapengut and Mizrach 2023). Blockchain displays decentralisation, immutability, transparency, anonymity, and auditability, contributing to its cost-effectiveness and efficiency (Zheng et al. 2017). Firstly, it is immutable, meaning that once a transaction is recorded on the blockchain, it becomes unalterable and resistant to tampering. This is achieved through unique cryptographic hashes in each block, derived from the contents of the previous block, making it practically impossible to modify any previous transactions without impacting the entire chain. Another notable feature of blockchain is its transparency. Since the ledger is shared among all participating nodes, it promotes openness and visibility of transactions. This transparency enhances trust and accountability within the system, as anyone can inspect and verify the recorded transactions. Furthermore, blockchain's distributed nature, where the ledger is maintained by a network of nodes rather than a single central authority, enhances the system's resilience to attacks or failures. This decentralised structure eliminates a single point of failure that could bring down the entire system (Drescher and Drescher 2017). Because all nodes maintain their copy of the ledger, perpetrating fraudulent transactions would require a malicious node to possess a majority of the computational power in the network. This situation is known as a 51% attack.

2.9.1 Benefits of Blockchain for Carbon Trading

Blockchain technology is emerging as a powerful tool for revolutionising carbon trading, offering a secure and transparent platform to address key market challenges. Its distributed ledger system ensures the immutability and security of transactions, which leads to reliable issuance and tracking of carbon credits (Saraji and Borowczak 2021). This fosters transparency and accountability, reduces the risk of fraud, and promotes accessibility for small and medium-sized enterprises (SMEs). Public blockchains lower entry barriers, enabling broader participation and a more inclusive market (Saraji and Borowczak 2021). This inclusivity is crucial for a diverse and dynamic carbon market. Moreover, blockchain facilitates efficient trading through Automated Market Makers

(AMMs). AMMs enable direct peer-to-peer trading of digitised carbon credits on the blockchain, eliminating intermediaries and reducing fees. This results in greater liquidity, a critical factor for a thriving market. By leveraging these benefits, blockchain creates a dynamic digital carbon credit ecosystem that connects all stakeholders, including the energy industry, project verifiers, liquidity providers, NGOs, concerned citizens, and governments. This fosters collaboration, resulting in efficient market operations. Ultimately, blockchain's enhanced transparency, accessibility, liquidity, and standardisation contribute to mitigating greenhouse gas emissions and combating climate change by creating a more trustworthy and efficient market.

2.9.2 Ownership and Traceability of Data

Data ownership is crucial in the digital age (Rotenberg 2020), especially when dealing with valuable assets like carbon offsets. While data can be easily replicated, blockchain technology offers a unique solution by providing a secure and transparent way to register, record, and trace data back to its origin. Each transaction on the blockchain is cryptographically secured through hashing, providing an immutable record of ownership and eliminating the risk of double-counting (Nakamoto 2008). This mirrors the function of carbon offset registries, which assign unique serial numbers to verified offsets and track their ownership transfers (Department of Energy - RSA 2016). This inherent transparency and immutability make the blockchain technology ideal for managing and tracking carbon offsets, ensuring secure ownership transfers and fostering trust in the carbon trading market.

3. Mudala Design

3.1 Overview of the Mudala Solution

Mudala, meaning "green" in Venda¹, is a South African exchange specialising in the trade of carbon credits. This system, enabled by blockchain technology, provides an easy-to-use, transparent, and reliable platform for companies to voluntarily purchase or sell carbon credits to offset their CO₂ emissions. Aligning with standard practices in global carbon markets, the Mudala exchange ensures each token represents one metric ton of CO₂ equivalent (CO₂e). This standardisation simplifies the trading process and enhances transparency, making it straightforward for participants to understand the environmental impact of their transactions.

The decision to equate one token to one metric ton of CO₂e is consistent with both traditional carbon credit standards and emerging blockchain-based solutions. Established programmes like the Verified Carbon Standard and the Gold Standard quantify each carbon credit as representing one metric ton of CO₂e reduced or removed from the atmosphere. Similarly, blockchain-based platforms such as the Toucan Protocol² and KlimaDAO³ adopt the same standard.

For Mudala, this approach ensures consistency and integration with existing carbon accounting systems, fostering stakeholder adoption and trust. For users, it provides ease of calculation, allowing them to easily assess their carbon footprint and the number of tokens needed to offset it, and ensures transparency, giving confidence that their offsets correspond to real and measurable emission reductions.

By linking carbon credits to the blockchain, Mudala facilitates decentralised trading compared to the traditional method of interacting directly with the government or

¹Venda or Tshivenda is a Bantu language and one of the official languages of both South Africa and Zimbabwe. It is primarily spoken by the Venda people also known as Vhavenda.

²Toucan Protocol is a blockchain-based carbon offset protocol that tokenises verified carbon units. Each Base Carbon Tonne (BCT) token represents one metric ton of CO₂e. More information can be found at: <https://docs.toucan.earth>.

³KlimaDAO is a decentralised autonomous organisation focusing on accelerating the price appreciation of carbon assets. It utilises tokenised carbon credits where one token equals one metric ton of CO₂e. More information can be found at: <https://www.klimadao.finance>.

regulator. This distributed ledger reduces entry barriers for small buyers seeking to offset their carbon footprint and ties a standard monetary value to each credit.

This chapter discusses Mudala's design, including functionalities needed by stakeholders and design considerations.

3.2 Participants in the System

We identify the following key actors within the Mudala ecosystem:

1. The Regulator: critical in issuing and validating carbon credit tokens while ensuring compliance with regulatory standards. This is essential in maintaining the system's integrity and ensuring that carbon reduction efforts are accurately accounted for. The Regulator may also facilitate trading by providing liquidity when needed, as it holds the reserve of tokens. The term regulator and validator are used interchangeably.

2. Buyers: play a critical role in the Mudala ecosystem by actively purchasing carbon credits to offset their emissions and contribute to global climate action. This includes companies from various industries, such as energy, who recognise their environmental impact and proactively seek solutions. These companies, including South African listed mining stocks like oil and gas companies, are major emitters and will face carbon taxes in the future. Engaging in the Mudala marketplace allows them to mitigate their impact and fulfil their environmental responsibilities by acquiring carbon credits.

3. Sellers: consist of renewable energy producers or companies that can undertake such projects. These sellers are incentivised to pursue green initiatives due to the financial rewards of allocating capital towards environmentally friendly projects. Examples include wind farms, tree-planting operations, CO₂ sequestration projects, and similar endeavours. By implementing these environmentally sustainable projects, sellers actively contribute to generating carbon credits.

3.3 Functional Requirements

Functional Requirements (FRs) define a product's specific actions and tasks to fulfil its core purpose (Robertson et al. 2012). These requirements outline the essential functions the product must perform to accomplish its intended work. Mudala's functional requirements and corresponding system actors are presented in Table 3.1.

Table 3.1: Key Functional Requirements for the Mudala Platform

FR ID	Functional Requirement (FR)	System Actor
FR1	Register as a member	Buyer, Seller
FR2	Authenticate as a member	Buyer, Seller
FR3	View member details	Buyer, Seller
FR4	Request carbon credits	Seller
FR5	Review credit requests	Validator
FR6	Approve or decline credit requests	Validator
FR7	Transfer approved credits to seller	Validator
FR8	Connect blockchain wallet	Buyer, Seller
FR9	Initiate and sign transactions using private key	Buyer, Seller
FR10	Mint new carbon credits	Validator

The functional requirements of Mudala are designed to mitigate the critical problems identified in existing cap-and-trade systems (see Section 2.8). Over-crediting is addressed through rigorous validation processes (FR5 and FR6), ensuring only verified and legitimate carbon credits are issued (FR10). The use of blockchain technology (FR8 and FR9) enhances transparency and traceability, resolving issues related to the unclear life cycle and validity of carbon credits, and preventing double-spending by recording immutable transactions. By facilitating direct interactions between buyers and sellers without intermediaries (FR1–FR4 and FR7), Mudala reduces high transaction costs and avoids wealth concentration among brokers. Additionally, by integrating the Validator role within the platform (FR5–FR7 and FR10), Mudala mitigates conflicts of interest associated with third-party verifiers, promoting impartiality and credibility in the verification process. Through these functional requirements, Mudala effectively addresses the shortcomings of current carbon trading systems, enhancing integrity and efficiency in the market.

To further simplify the Mudala system’s functional requirements, we employ case modelling, as highlighted by [El-Attar and Miller \(2008\)](#). This widely used approach drives the design phases of software projects, facilitating the practical description of a system’s functional requirements. A use case diagram visually represents how different actors interact with the system’s tasks and the relationships between those tasks. Figure 3.1 below presents a use case diagram summarising the core functional requirements identified for Mudala.

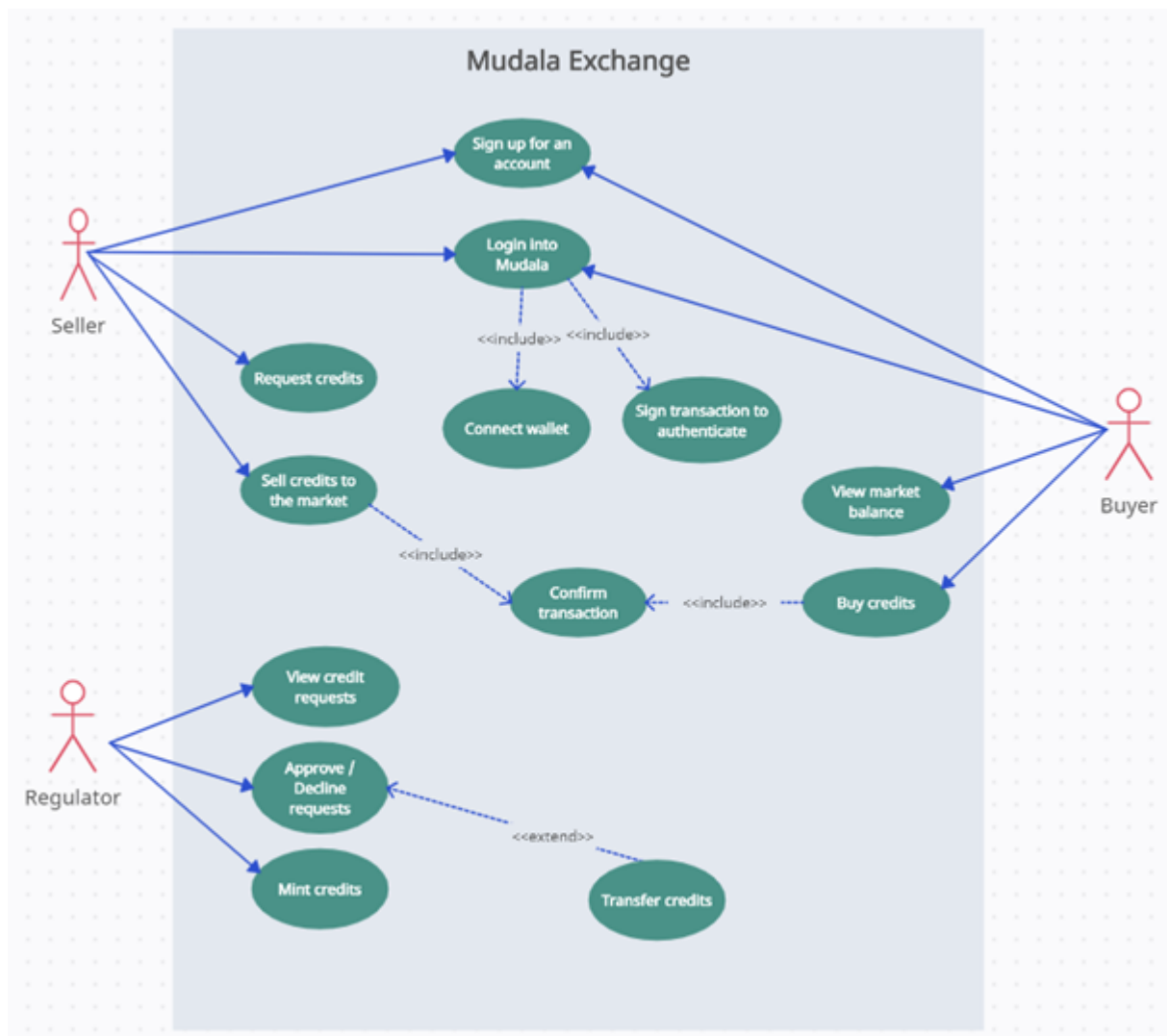


Figure 3.1: The use case diagram illustrating how the Mudala system actors interact with key system functionality, such as connecting their wallets, selling credits to the marketplace, and signing transactions.

3.4 Non-functional Requirements

Non-functional requirements (NFRs) define how effectively the Mudala platform performs its tasks, ensuring it is attractive, usable, fast, reliable, and secure (Robertson et al. 2012). These requirements guarantee meeting the client's expectations regarding the platform's quality and performance characteristics. Table 3.2 on the following page presents the identified NFRs for Mudala.

Table 3.2: Non-functional Requirements for the Mudala Platform

NFR ID	NFR Type	Description
NFR1	Performance	Fast response times: Users must experience quick responses for member registration, authentication, and credit request processes.
NFR2	Security	Data protection: User data, including member details and credit transactions, must be securely stored and protected from unauthorized access.
NFR3	Usability	Intuitive user interface: The platform must offer a user-friendly and intuitive interface, enabling easy navigation and interaction for all user types (buyers, sellers, validators).
NFR4	Reliability	High availability: The application must ensure high availability, guaranteeing minimal downtime and accessibility for users.
NFR5	Scalability	Handle growing user base: The system must scale efficiently to accommodate an increasing number of users, transactions, and data without compromising performance. Explore hybrid solutions combining traditional databases and blockchain to address potential scalability limitations.
NFR6	Compliance	Regulatory adherence: The application must comply with relevant regulatory standards and requirements for carbon credit trading.

3.5 Criteria For Listing A Carbon Offset Project On Mudala

Mudala defines the following criteria for listing carbon offset projects, adapted from the Carbon Offsets Paper ([National Treasury 2014](#)):

- i) **Geographic Scope:** Mudala exclusively accepts carbon offset credits from projects located within South Africa. This fosters domestic development and ensures that the positive environmental impact directly benefits the nation.
- ii) **Focus on Non-Regulated Activities with Robust Verification:** Mudala targets projects involving activities not directly regulated under the carbon tax to avoid double-counting emission reductions and ensure additionality. To mitigate risks associated with projects outside regulated industries, Mudala implements stringent verification and compliance measures:
 - **Third-Party Verification:** Projects must be verified by accredited independent auditors.

- **International Standards Compliance:** Adherence to standards like the Verified Carbon Standard or the Gold Standard is mandatory.
 - **Continuous Monitoring:** Ongoing reporting and monitoring are required to maintain transparency and prevent greenwashing.
- iii) **Inclusion of Tax-Exempt Entities Outside Regulated Industries:** Entities exempt from the carbon tax because they operate outside regulated industries are encouraged to implement emission-reduction projects and sell their generated credits to those subject to the tax. This approach fosters broader participation and additional emission reductions.
- iv) **Low-Carbon Transition and Climate Impact Assessment:** Mudala seeks projects that contribute to South Africa's transition to a low-carbon economy by reducing greenhouse gas emissions and addressing climate change challenges. Projects must:
- **Quantify Emission Reductions:** Use internationally accepted methodologies to calculate emissions reductions.
 - **Undergo Third-Party Verification:** Verification by accredited auditors ensures the credibility of the emission reductions.
 - **Align with National Climate Goals:** Demonstrate how they support South Africa's climate change policies and targets.
- v) **Alignment with Developmental Priorities:** Projects must contribute to South Africa's established developmental priorities. These include:
- Fostering energy efficiency
 - Promoting renewable energy
 - Enhancing public transport and its energy efficiency
 - Advancing sustainable agriculture and forestry practices
 - Improving waste management

This ensures alignment with national development objectives and creates co-benefits beyond carbon reduction. These requirements ensure that Mudala's listed projects deliver tangible environmental benefits, contribute to national goals, and promote broader participation in carbon reduction efforts.

3.6 Blockchain System Design Considerations

Choosing the right technology for the Mudala Carbon Credits Exchange is critical for success. While blockchain technology seems promising, we carefully assess its suitability for the platform's core functions and user needs. This section uses a checklist adapted from [Xu et al. \(2016\)](#) to evaluate whether blockchain best fits Mudala. We make

an informed decision about the platform’s architecture by analysing critical factors like the number of participants, asset type, and transaction requirements. Importantly, we determine if blockchain offers significant advantages over traditional database solutions for Mudala’s specific context.

Table 3.3: A completed checklist to establish whether blockchain technology is an appropriate solution for the Mudala Carbon Credits Exchange.

Question	Response
Are there multiple actors with distinct interests contributing?	Yes. There are different participant groups, including buyers, sellers, and regulators.
Is there a digitally representable asset?	Yes. The asset is carbon credits, which are tokenised on the blockchain.
Is there a need for a final and immutable transaction record?	Yes. Given the diverse participants and the need for transparent carbon credit trading, an immutable transaction record is crucial.
Are there high expected transaction volumes?	No. Depending on the trading frequency, the transaction volume is manageable.
Is there a potential for removing intermediaries?	Yes. By utilising blockchain technology, intermediaries can be reduced, leading to cost savings.
Are there conflicting incentives or interests between actors?	Yes. Participants seek transparent and traceable trading to prevent fraudulent behaviour.
Should there be full data transparency towards external actors?	No. Transactions are primarily private among participants, with potential access for regulatory purposes.
Should there be permissioned access to the system?	Yes. Only verified participants should transact, with different roles requiring verification.

Based on the analysis within this section, blockchain technology demonstrates potential suitability for the Mudala Carbon Credits Exchange. Its ability to facilitate secure, transparent, and immutable transactions aligns well with the platform’s requirements.

3.7 Data Model of the Mudala System

Mudala’s carbon exchange platform leverages a hybrid data model that combines the transparency and security of blockchain technology with the efficiency and scalability of

a relational database. This section details the data model for two key tables: *RegisteredMembers* and *CreditRequests*. The *RegisteredMembers* table stores essential information about platform members, while the *CreditRequests* table tracks the history of credit requests submitted by members to the regulator.

Table 3.4: Data model and attribute descriptions for the *RegisteredMembers* and *CreditRequests* tables in the Mudala carbon exchange platform. *RegisteredMembers* captures essential information about platform members, including company name, wallet address, member type, project ID, tax ID, and email address. *CreditRequests* maintains a record of credit request history, including the requested amount, status of the request, and the date it was made.

Table Name	Data Attribute	Description	Example
RegisteredMembers	pk (Primary Key)	Unique ID for member registration	22
	companyname	Company name of the member	Green Co
	walletaddress (PK)	Unique ID for member's wallet address	2trhjs7kjdt6igxghdyd
	membertype	Type of member (e.g., buyer or seller)	Seller
	projectid	Unique ID for member's project (if applicable)	53
	taxid	Tax ID of the member (if applicable)	87
	Email	Email address of the member	seller@gmail.com
CreditRequests	pk (Primary Key)	Unique ID for credit request entry	1
	memberid (Foreign Key)	Foreign key referencing the <i>RegisteredMember</i>	22
	amount	Requested amount of credit tokens	30
	status	Status of the credit request	Pending
	date	Date of the credit request	20/09/2023

The data model presented in this section provides a foundation for securely managing member data and tracking credit requests within the Mudala platform. This design ensures that the platform can effectively manage its members and facilitate carbon credit transactions while maintaining data security and integrity.

4. Mudala Implementation

We implement Mudala¹ as a hybrid web/blockchain application. It is deployed in a cloud environment and integrated with the Algorand TestNet for development and testing. The cloud environment - Render ensures global accessibility and provides users with a seamless software-as-a-service experience. This chapter discusses the implementation of the Mudala carbon credits exchange, its architecture, and how it works.

4.1 System Architecture

The following diagram presents the high-level system architecture of the Mudala platform.

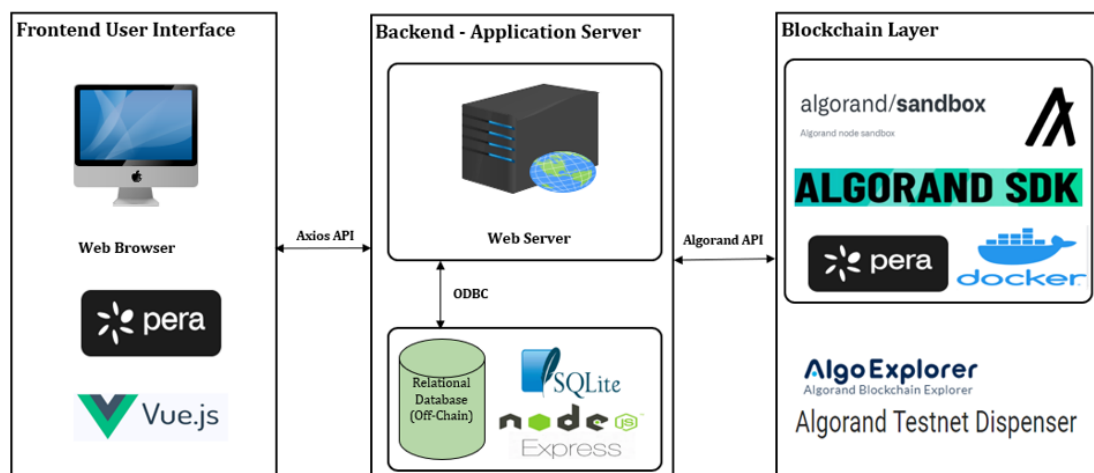


Figure 4.1: High-level system architecture diagram showcasing the key components and layers of the Mudala carbon exchange platform. The architecture includes a User Interface layer developed using Vue.js for a responsive and user-friendly web application, an Application Server layer built with Express to connect to the SQLite database and handle data insertion and retrieval, and a Blockchain Layer integrating the Mudala web application with the Algorand blockchain network for secure and transparent carbon credit management.

¹Mudala Platform:<https://mudala-carbon-exchange.onrender.com>

The key components of the architecture include:

4.1.1 Frontend - User Interface

Users directly interact with Mudala through a responsive and intuitive web application built with Vue.js, a popular JavaScript framework.

Vue.js simplifies development, enabling the creation of single-page applications (SPAs) and interactive user interfaces (UIs) with several key advantages:

- i) **Low learning curve:** Easy to learn for developers with basic knowledge of web technologies.
- ii) **High performance:** Delivers faster app launches than React and AngularJS.
- iii) **Rich toolkit:** Includes Vue CLI 3, testing tools, and support for TypeScript and Babel.
- iv) **Consistent design:** PrimeVUE library ensures a unified look and feel.
- v) **User comfort:** The customisable dark mode option enhances the user experience.

Easy Navigation with Vue Router: The application seamlessly navigates between four key pages: landing page, member page, validator page, and market page, facilitated by Vue Router.

Efficient Data Communication with Axios: Axios handles data requests between the web application and the backend API, ensuring smooth data exchange for storing and retrieving information from the SQLite database.

4.1.2 Backend - Application Server

The application server serves as the central engine, driving the core logic of the Mudala carbon exchange platform. It acts as the platform's brain, efficiently processing data, facilitating member registration and data retrieval, and ensuring smooth communication between frontend web pages and the underlying SQLite database.

Express: is chosen to connect the front end and the SQLite database. Upon startup, the Express API initialises the database connection. It provides routes for platform members to register and submit information, which is then stored in the database. Additionally, seller requests to credit their wallets with carbon tokens are handled through designated routes.

SQLite database: is a repository for registered token buyers (businesses) and sellers (carbon offsetting projects). It stores user details provided through the frontend application, serving as an additional audit trail for regulators. This information

includes organisational names, wallet addresses, email addresses, and project certification numbers (for sellers). While the blockchain provides a comprehensive transaction history, the SQLite database enables faster and simpler querying of transactions and user information.

4.1.3 Blockchain Network - Algorand

The blockchain layer forms a crucial part of the architecture. This layer handles the creation, transfer, and verification of carbon credits on the Algorand blockchain, ensuring transparency, immutability, and security within the Mudala platform's carbon credit ecosystem. It consists of a decentralised network of computer nodes that work collaboratively. This layer guarantees the platform's security and transparency by maintaining an unchangeable and reliable ledger of transactions. Cryptographic techniques achieve this by verifying and validating transactions without a central authority.

4.1.3.1 Algorand Blockchain

Mudala is integrated into the Algorand blockchain. Founded in 2017 by Turing Award winner Silvio Micali, Algorand is an open-source, public blockchain utilising proof-of-stake for consensus, offering an energy-efficient alternative to proof-of-work systems (Chen and Micali 2016). Its native currency, Algos, empowers users to participate in validating transactions and securing the network. With its non-forking design, only one block is finalised per round, enabling transaction confirmation in under five seconds. Moreover, Algorand enables users to effortlessly convert real-world assets such as carbon credits into Algorand Standard Assets (ASAs), utilising tokenisation.

Tokenisation involves creating a digital representation of a tangible asset on a decentralised ledger system (Hileman and Rauchs 2017). Tokens are generally classified into two primary forms: fungible (identical and interchangeable) and non-fungible (unique). On the Algorand blockchain, tokens are known as ASA, and they can be easily generated using the Algorand Software Development Kit (SDK) without necessitating the creation of smart contracts, as is the case with other blockchains like Ethereum. During the creation process, a newly minted asset (i.e., token) is defined by various parameters, including the creator's address, asset name, unit name, total supply, and decimals, among other necessary parameters.

4.1.4 Why Algorand Blockchain

Algorand is the chosen blockchain network for this research for several reasons:

- i) **Lower gas fees:** Transactions on Algorand are significantly cheaper than alternatives like Ethereum or Bitcoin, making it more affordable and incurring minimal costs (currently: 0.001 Algos 0.0000982 USD 0.00183 ZAR).
- ii) **Energy-efficient PoS:** Unlike Bitcoin's energy-intensive Proof of Work (PoW) mechanism, Algorand uses a Proof of Stake (PoS) approach to minimise its environmental impact.
- iii) **High transaction speed and low cost:** Transactions on Algorand are finalised in under five seconds.
- iv) **Carbon neutrality:** Algorand's claim of a carbon-neutral blockchain², aligns perfectly with Mudala's goals of promoting green and efficient emissions reduction. Mudala's integration with Algorand ensures that the platform aligns with modern low-carbon standards essential for effective emissions reduction initiatives. By leveraging Algorand's innovative, energy-efficient, and carbon-neutral blockchain technology, Mudala promotes a sustainable approach to environmental responsibility.

4.2 How it Works

The Mudala carbon exchange platform, depicted in Figure 4.2, operates as follows: Member registration and authentication details are excluded from the diagram for simplicity and can be found in Appendix B.

- i) **Request credits:** Sellers initiate the process by clicking 'Send Request.' The system uses the pre-populated member ID to identify the sellers.
- ii) **Transfer credits:** Regulator checks the validity of the request and determines the number of tokens that should be released to the requestor (owner of a carbon offset project) by inspecting the provided certificate numbers
- iii) **Sell Credits:** Sellers connect their wallets to the Mudala Exchange and transfer the credits to the market account.
- iv) **Receive Algos:** Algos are then transferred from the market account to the seller's account.
- v) **Buy Credits:** Buyers connect their wallets and purchase carbon credits from the exchange.
- vi) **Receive Algos:** The Mudala exchange account receives the corresponding algos.

²Algorand carbon neutrality: <https://www.algorand.foundation/news/carbon-neutral>

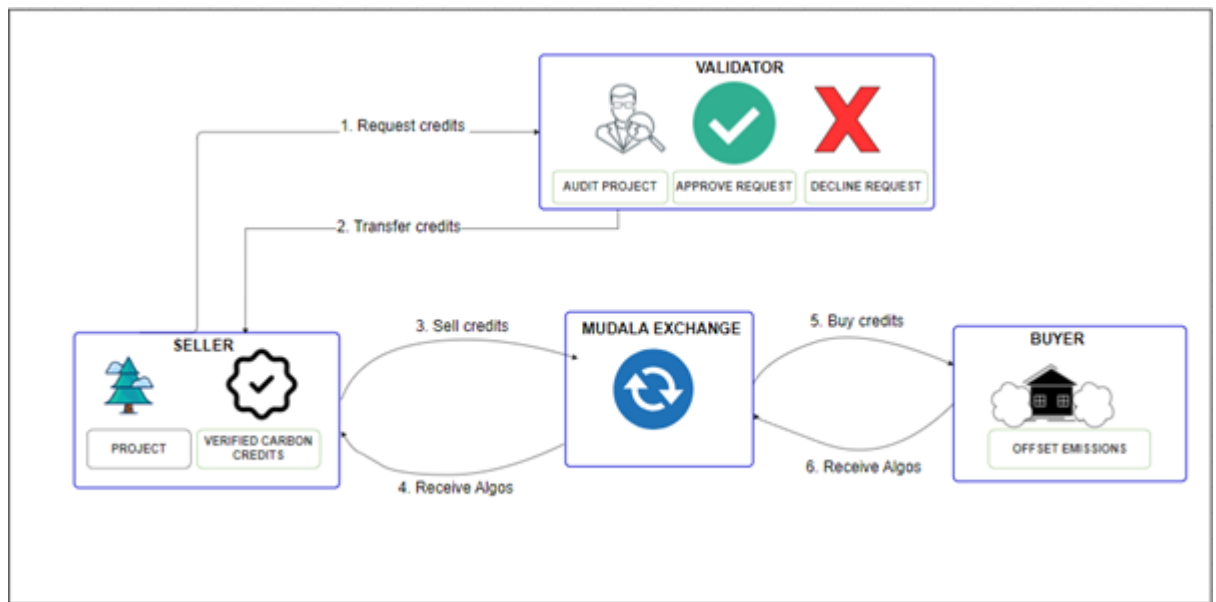


Figure 4.2: A visual illustration of how the Mudala system operates. The key features of the Mudala carbon exchange platform, including Member Registration, Member Authentication, Project Validation, and Carbon Credits Trading, work seamlessly together to provide an efficient and secure environment for members to participate in carbon credits trading while ensuring transparency and accountability throughout the process.

4.2.1 Key Features of Mudala

The Mudala carbon exchange platform offers several key features, which are outlined below:

Member Registration: To register, prospective users provide their organisation name, wallet address, and email address and select their account type (buyer or seller). Once the registration is complete, a unique membership code is issued.

Member Authentication: Members are then authenticated by logging in to Mudala via Pera Wallet and signing a zero Algo transaction. If confirmed as a seller, the page refreshes to display details such as token balance and credit request history. If there are no pending requests, sellers can request additional tokens from the Regulator.

Token Minting: As the entity overseeing the marketplace, the Regulator is responsible for minting new carbon tokens. Mudala has two key accounts for minting Carbon Credits Tokens (CCT): the creator and reserve accounts. Given that once tokens are minted, the total supply cannot be changed, a significant number of tokens are minted upfront and stored in the reserve account. The reserve account manages the total supply of CCT and can transfer tokens to the creator account if needed. These tokens represent verified carbon credits from sellers who have undergone the validation process. The Regulator ensures that each minted token corresponds to a legitimate reduction of carbon

emissions. Furthermore, tokens in Mudala have single ownership, ensuring transparency, which prevents double counting - an issue in existing markets. To simplify this project, we assume that a regulatory body has validated the carbon offsetting projects (for which carbon credits are minted) and deemed them appropriate for listing on the exchange.

Carbon Offset Project Validation: Regulators assess and approve token requests from sellers, ensuring carbon credit credibility within the exchange. They verify documentation and evidence for compliance with standards. After validation, they initiate a one-way token transfer to seller wallets. This process only involves the issuance of carbon tokens as recognition of emissions reductions, and no funds are transferred.

Carbon Credits Trading: : Buyers and sellers trade tokens on the market page. Members connect to Pera Wallet, select accounts, and view balances. Sellers check balances and sell tokens while buyers purchase them. Pera Wallet confirms transactions and updates token balances accordingly.

The use of blockchain ensures that each carbon credit is uniquely tokenized and tracked in real time, preventing any risk of double counting. This guarantees that carbon credits are only issued and traded once, with full traceability from creation to redemption.

5. Mudala Evaluation

This section evaluates the Mudala platform in addressing the limitations of existing carbon markets and its potential contribution to achieving SDG 13. It explores three main research questions:

RQ1: Can blockchain address limitations of existing markets (such as trust and transparency issues, over-crediting, and high transaction costs)?

RQ2: How does Mudala increase accessibility for developing countries?

RQ3: How do Algorand features contribute to international collaboration?

With three corresponding objectives:

Obj1: Develop Mudala POC and assess its effectiveness

Obj2: Evaluate Mudala's effectiveness in accessibility and emission reduction

Obj3: Analyse Algorand features' contribution to Mudala's functionality.

5.1 Evaluation of Research Questions and Objectives

Now that we understand the research questions, objectives, and existing market problems, let us validate the solutions proposed by the Mudala platform.

RQ1 Obj1: Can Blockchain Address Existing Market Limitations?

Mudala's decentralised architecture promotes transparency through immutable transaction records stored on the blockchain. This public ledger ensures that all transactions are verifiable and traceable, preventing manipulation or fraudulent activity. Additionally, token creation is strictly linked to verified emission reductions, effectively mitigating over-crediting. Each token represents a single unit of carbon offset, preventing the issuance of more credits than actual reductions achieved. The platform's decentralised structure also reduces transaction costs. By minimising intermediaries and leveraging lower fees on the Algorand blockchain, Mudala makes carbon trading more affordable. This increased affordability expands market access, encouraging broader participation and potentially attracting smaller players previously excluded due to high costs. Further-

more, Mudala supports renewable energy adoption by prioritising carbon offset projects focused on clean energy solutions. Facilitating verified carbon credit trading for these projects directly contributes to emission reduction, aligning with the core objective of SDG 13.

RQ2 Obj2: Enhancing Accessibility for Developing Countries

Mudala's fractionalised carbon credits lower entry barriers, making the market accessible to small buyers and businesses in developing countries – this promotes broader participation from previously excluded groups. Moreover, reduced transaction costs achieved through the platform's decentralised nature further enhance affordability for developing countries. By eliminating unnecessary fees, Mudala increases the efficiency of carbon trading and makes participation more accessible. Furthermore, the platform's specific focus on South Africa addresses the unique needs and challenges a developing nation faces in transitioning to a low-carbon economy. This targeted approach aligns with SDG 13, contributing to South Africa's efforts to reduce greenhouse gas emissions and promote sustainable development.

RQ3 Obj3: Fostering Collaboration and Emission Reduction

Mudala leverages blockchain technology's inherent transparency and verifiability to foster trust among participants, encouraging cross-border collaboration. Its immutable and tamper-proof public records solidify this international trust and cooperation. Additionally, decentralisation eliminates the need for central authorities, further promoting international cooperation by enabling participation from diverse stakeholders across various countries.

The energy-efficient Proof-of-Stake consensus mechanism employed by Algorand minimises the platform's environmental impact, aligning with global emission reduction goals. Compared to other blockchain technologies, Algorand's reduced carbon footprint contributes to the overall sustainability of Mudala's operations.

Finally, Mudala addresses problems like double spending and conflict of interest with verifiers. The platform's single ownership and on-chain tracking prevent the duplicate use of tokens, eliminating the possibility of double counting. Additionally, independent third-party validators ensure objectivity and fairness by utilising clear criteria and automated processes, mitigating potential bias and aligning with the research objective of transparency.

Overall, the Mudala platform offers promising solutions to address critical challenges in existing carbon markets. However, a comprehensive validation requires further data analysis, user feedback, and real-world implementation results.

5.2 Blockchain Solution Validation

The suitability of blockchain for Mudala depends on its ability to address specific requirements, leveraging its distributed and automated nature compared to traditional databases. However, blockchain solutions present trade-offs compared to centralised databases, including scalability, capacity, and latency (Schletz et al. 2020). To systematically evaluate Mudala’s carbon credit marketplace, we adopt a decision framework from Schletz et al. (2020), integrating fit considerations and modifying existing models to align with climate policy needs. Figure 5.1 depicts the adapted evaluation criteria for blockchain sustainability applied to the Mudala platform.

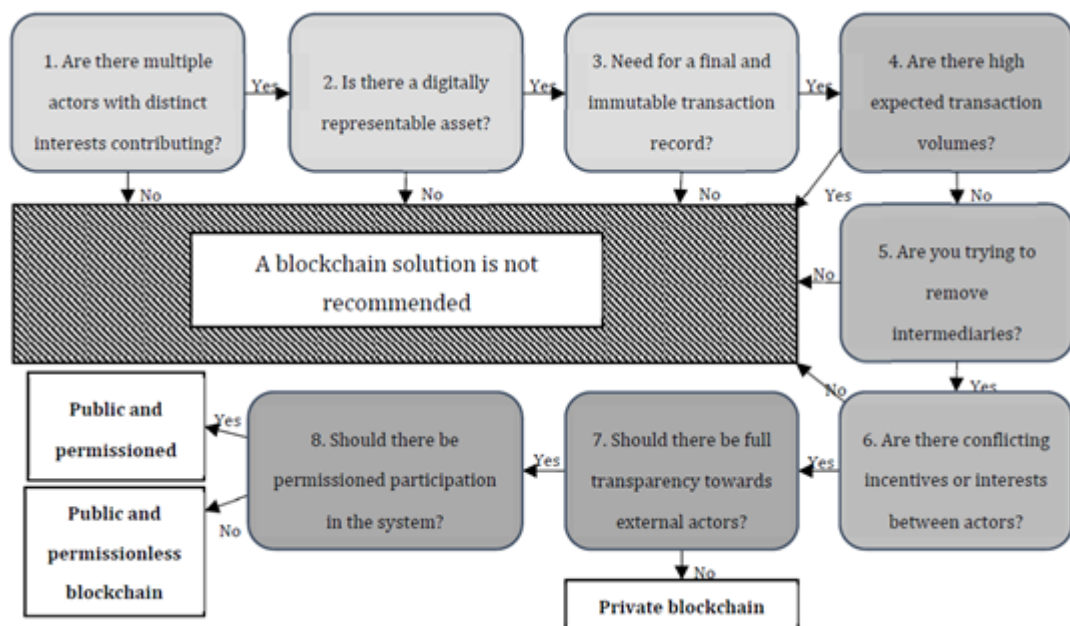


Figure 5.1: Evaluation Criteria for Suitability of Blockchain Technology to the Mudala Carbon Credits Marketplace. Adapted from Schletz et al. (2020). The framework includes eight classifiers, starting with overall blockchain applicability (classifiers 1 to 3), assessing technical performance requirements (classifiers 4 to 6), and determining the appropriate blockchain type based on governance and data accessibility (classifiers 7 and 8).

In the following, we examine each classifier based on the requirements of the Mudala carbon credits exchange.

Multiple Actors Contributing:

Blockchain’s strength lies in enabling a network of connected nodes to reach consensus even in scenarios with conflicting data or mistrust (Schletz et al. 2020). This ensures that a single, unified record is maintained across all participants (Zachariadis, Hileman, and Scott 2019). This data-sharing method mitigates risks associated with single points

of failure and information imbalances (Niya et al. 2018).

In the context of Mudala's carbon credit market, blockchain facilitates the exchange of credits between buyers responsible for emissions and sellers generating carbon credits. Regulatory bodies verifying projects and issuing certifications are also part of this ecosystem. This dynamic collaboration forms the foundation of the decentralised system.

Digitally Representable Asset:

Carbon credits undergo tokenisation on the Algorand blockchain. This process creates standardised tokens, each representing one metric ton of CO emissions. These tokens are interchangeable, simplifying carbon credit valuation and enabling straight-forward trading. Tokenisation also offers inherent benefits like automated transaction processing, streamlined clearing and settlement, and a transparent, traceable historical record (OECD 2020). The Mudala platform facilitates the smooth conversion of carbon credit tokens into Algos, the native cryptocurrency of the Algorand network. Mudala aligns carbon credit tokens on the blockchain with specific mitigation targets. This design enables seamless conversion of digital carbon credits into monetary units (Niya et al. 2018).

Final State and Immutable Record:

Transactions are systematically recorded chronologically on the blockchain, creating an unalterable historical record. This traceability, built on mathematical principles, enhances trust (Schierreck 2017; Zheng et al. 2017). As the blockchain grows, altering a block becomes impossible, ensuring information integrity over time. This reliability is particularly valuable for audits (Glaser 2017). Immutability guarantees consistent and transparent records for carbon credit tokens, addressing existing market concerns about transparency, over-crediting, double spending, and unclear life-cycles. This permanent and unchangeable record improves transparency and accountability, allowing for easy identification of fraudulent behaviour and tracking of all involved actors (Dai and Vasarhelyi 2017). The Mudala marketplace, built on the Algorand blockchain, records and tracks tokens representing our approved projects. This system prevents double-counting and ownership conflicts by ensuring each token has a single, verifiable owner.

High Transaction Volumes:

Compared to centralised databases, blockchain systems often experience limitations in transaction throughput, data storage capacity, and speed (Pedersen et al. 2019). This issue, known as blockchain scalability, becomes particularly problematic when storing larger files and images, as it increases the amount of data needed to keep the network synchronised (Schletz et al. 2020). Fortunately, past experiences with market mechanisms like the Kyoto Protocol and the EU-ETS demonstrate that reports primarily consist

of text or tabular documents (Schletz et al. 2020). Franke et al. (2020) estimate an approximately threefold increase in peak transaction volume compared to the Kyoto mechanism, reaching 1.2 billion annually or an average of 36 transactions per second – still manageable for most blockchains. To address scalability, Mudala employs a hybrid and redundant data storage layer. While the blockchain guarantees an immutable transaction history, Mudala also uses a SQLite database for faster querying of credit requests and user data. This database captures user-provided information like organisation name, wallet address, email address, and project certification numbers. Additionally, storing large files in off-chain databases can alleviate scalability concerns (Xu et al. 2016).

Removing Intermediaries: Centralised databases rely on a few network authorities to manage and make decisions (Schletz et al. 2020). For example, the UNFCCC controls the CDM registry in the CDM scheme (Dunkel 2018). While Parties trust the UNFCCC, a single central authority creates a potential single point of failure (World Bank Group 2018). In contrast, Mudala runs as a decentralised network. Outside of the platform operator, no single authority controls the entire system; a network of participating users collectively manages carbon credit transactions and records. This approach enhances platform reliability and resilience, offering increased security and transparency.

Conflicting Incentives of Actors:

Blockchain technology builds trust through decentralised data storage and governance involving various nodes. In Schletz et al. (2020) case study, these nodes represent actor groups connected to Article 6.2¹, including national parties, the UNFCCC secretariat, and others. However, under Article 6.2, parties have a natural financial incentive to potentially exaggerate their carbon reduction supply (ITMOs) to meet NDC targets or for financial gain (Leonhard 2017). Similar challenges plagued Track 1² of the Kyoto Framework’s Joint Implementation mechanism, leading to criticism and poor environmental integrity ratings (Kollmuss et al. 2015). To address these concerns, Mudala leverages blockchain technology. The platform enforces tamper-resilience and enhances transparency and auditability, ensuring unit quality despite varying motivations. Using the Algorand blockchain, Mudala automatically implements Article 6.2 guidelines, preventing issues like double-counting. Additionally, by replacing project-developer-paid verifiers with an independent third-party verification mechanism, Mudala tackles potential conflicts of interest and boosts credibility.

Public or Private Transactions: Having validated the suitability of blockchain,

¹Article 6.2 of the Paris Agreement provides a way for countries to collaborate on climate action. This includes emissions trading to help countries meet their emission reduction goals. Several UN agencies are involved in managing and supporting these cooperative efforts.

²Joint Implementation:<https://unfccc.int/process/the-kyoto-protocol/mechanisms/joint-implementation>

we consider the desired governance design for system transparency and participation openness. Blockchains can operate in various modes: some, like Bitcoin, Algorand, or Ethereum, are public, allowing everyone to view activity. Others, like Hyperledger Fabric or Corda, require permission for access (Pedersen et al. 2019; Schletz et al. 2020). In Mudala, transactions remain pseudo-anonymous among participants, with the possibility of regulatory access for oversight. This approach prioritises confidentiality while enabling necessary external scrutiny.

System Permissioning: Building on the need for both transparency and regulated participation, access control becomes another crucial design consideration. Systems can range from fully open to restricted (Schletz et al. 2020). Open systems allow anyone to join and participate in decision-making, while restricted systems are controlled by select groups of authorities (Pedersen et al. 2019). Mudala adopts a permissioned approach. Only verified participants with varying access levels, depending on their roles, can transact on the platform. This balances the need for control and oversight with the decentralised nature that fosters transparency and trust.

5.3 Cost Efficiency of Mudala

To assess whether Mudala offers cost advantages over traditional carbon markets, this section compares the costs involved in EU ETS, Voluntary Carbon Markets (VCM), and Mudala. As discussed in Section 2.8, traditional carbon markets often lack transparency. These markets involve hidden fees and complex layers of intermediaries, including brokers, verifiers, and administrative bodies, making cost comparisons difficult due to inconsistent and opaque fee structures (Battocletti, Enriques, and Romano 2024).

Cost Components in Traditional Carbon Markets

Before diving into specific cost components, it is important to note that due to the lack of transparency in these traditional markets, it is challenging to obtain accurate cost data. Fees can vary widely depending on factors such as market conditions, transaction size, and the specific broker involved, further complicating comparisons between platforms (Kollmuss et al. 2008).

Broker Fees:

In the EU ETS, broker fees typically range from 0.1% to 1% of the transaction value due to high liquidity and competition. In VCM, broker fees can range from 3% to 10%, averaging around 5%, as the market is less liquid and involves greater transaction complexities (Battocletti, Enriques, and Romano 2024).

Administrative Fees:

Administrative fees in the EU ETS include exchange fees and compliance costs, estimated at around \$0.20 per tonne. [Cludius et al. \(2019\)](#) discuss how administrative burdens within the EU ETS can reduce its cost efficiency, particularly due to the complexities involved in compliance and verification processes. In the VCM, administrative fees include registry fees and documentation, estimated at around \$0.30 per tonne ([Battocletti, Enriques, and Romano 2024](#)).

Transaction Fees:

Transaction fees in the EU ETS can vary but are estimated at around \$50 per transaction. VCMs have similar transaction fees. In contrast, the Algorand blockchain used by Mudala has transaction fees of approximately 0.001 Algos per transaction, which is approximately \$0.0001. [Naegele \(2018\)](#) highlights how firm-level complexities and quantile variations in transaction costs create inefficiencies that blockchain platforms such as Mudala aim to eliminate.

Assumptions for Cost Analysis

- **Transaction Size:** Purchase of carbon credits equivalent to 1,000 tonnes of CO₂e.
- **Price per Tonne:** \$10.
- **Total Credit Value:** \$10,000.
- **Broker Fees (Mudala):** 1% charged by Mudala to ensure sustainability.
- **Verification Costs:** Paid by the seller in all markets.

Table 5.1: Cost Comparison Between Traditional Carbon Markets and Mudala

Cost Components	EU ETS	VCM (VCS)	Mudala
Credit Value	\$10,000	\$10,000	\$10,000
Broker Fees	\$100 (1%)	\$500 (5%)	\$100 (1%)
Administrative Fees	\$200	\$300	\$0
Transaction Fees	\$50	\$50	\$0.0004
Total Cost to Buyer	\$10,350	\$10,850	\$10,100
Total Savings with Mudala	\$250 (2.42%)	\$750 (6.91%)	—

Analysis

The cost comparison in Table 5.1 shows that:

- **Mudala vs. EU ETS:** Mudala saves buyers approximately \$250, which is approximately 2.42% compared to the EU ETS.
- **Mudala vs. VCM (VCS):** Mudala offers savings of about \$750 or 6.91% compared to VCM.

This cost analysis highlights that Mudala provides significant savings compared to traditional carbon markets, especially in terms of transaction fees and administrative fees. By eliminating intermediaries and using blockchain technology, Mudala streamlines the carbon trading process.

Beyond these cost advantages, Mudala also tackles the nonmonetary challenges that often plague traditional carbon markets, such as a lack of transparency, slow transaction speeds, and insufficient auditability. With blockchain, there is no need for intermediaries, allowing direct buyer-seller interactions and enabling real-time verification and comprehensive audit trails, ensuring complete transparency throughout the process. For larger transactions or future scaling, these savings could become even more substantial, offering a strong incentive for market participants to embrace the Mudala system. The speed of blockchain transactions is in stark contrast to the slower methods of traditional markets, which typically depend on multiple intermediaries to finalise deals. While this initial analysis points to promising cost efficiencies, future studies could delve deeper, using real-world data to provide deeper insights into Mudala's performance in various market conditions.

5.4 Comparison of Mudala with Existing Solutions

By analysing the current carbon market landscape, including both traditional and emerging decentralised solutions, we gain a deeper understanding of Mudala's position. Our tiered analysis (summarised in Table 5.2) reveals several areas where Mudala differentiates itself:

Table 5.2: Comparison of Carbon Credit Platforms based on Criteria: Blockchain Platform Used, Carbon Project Type, Token Standardization, Carbon Standard, Geographical Location.

Criteria / Platform	Mudala	Toucan Protocol ³	KlimaDAO ⁴	Flowcarbon ⁵	Credible Carbon ⁶
Description	Allows firms to trade fungible carbon credit tokens on a blockchain for CO2 emissions offset	Offers a blockchain platform for trading tokenized Voluntary Carbon Market (VCM) credits	Integrates Web3 tech into carbon markets for widespread participation in the emerging economy	Enhances carbon lifecycle accuracy and transparency by supporting financing for emissions-reducing projects	A registry for transparent access to global carbon markets, benefiting poverty-alleviating African projects
Blockchain	Algorand Blockchain	Ethereum, Polygon and Celo	Ethereum	Celo	Not Using Blockchain
Carbon Project Type	Nature Based, Renewable Energy	Nature Based	Nature Based	Nature Based	Waste to Energy, Community Projects
Standardisation of Tokens	CCT	TCO2	KLIMA	GNT	Not Applicable
Carbon Standard	Credible Carbon Standard	Verra and Gold Standard	Verra and Gold Standard	Gold Standard	Credible Carbon Standard approved by UNFCCC
Geographical Location	South Africa	United States	United States	United States	South African

Here are the key takeaways:

Platform Technology: Mudala's adoption of the modern, carbon-neutral Algorand blockchain sets it apart. Competitors' choices (Ethereum, Polygon, Celo) have varying degrees of energy consumption with Polygon and Celo generally considered eco-friendly. Credible Carbon, as a non-blockchain solution, has no associated carbon footprint.

Project Scope: Mudala, like its competitors, demonstrates adaptability by supporting

diverse carbon projects (nature-based, renewable energy, etc.). This highlights its potential to contribute to various sustainability goals. Tokenization: Mudala's use of standardised tokens, similar to Toucan Protocol, KlimaDAO, and Flowcarbon, enhances transparency and traceability – key advantages of blockchain-based solutions. Credible Carbon lacks this ability.

Standards Alignment: Mudala plans to adopt the Credible Carbon Standard approved by the UNFCCC, establishing a credible foundation for its carbon credits. This ensures that the credits traded on Mudala are recognised under international compliance mechanisms. Looking ahead, Mudala intends to collaborate with internationally recognised standards such as Verra and Gold Standard, further aligning itself with industry benchmarks and broadening its appeal in the global carbon market. Additionally, Mudala's credibility will be enhanced through its collaboration with the University of Cape Town's Energy Research Centre (ERC)⁷. The ERC provides expert guidance on energy policy and carbon market mechanisms, ensuring that Mudala's operations fully align with South Africa's national climate objectives and regulatory requirements. This partnership strengthens Mudala's commitment to local sustainability efforts and reinforces trust among participants by demonstrating adherence to national and international standards.

Market Focus: Mudala stands out as the only blockchain-enabled carbon credit solution catering specifically to the South African market. Its local focus, compared to the US-based Toucan Protocol, KlimaDAO, and Flowcarbon, presents a unique market opportunity.

Overall, Mudala aims to synthesise the strengths of existing platforms by adopting a single standardised token format for enhanced transparency and comparability within the market. Additionally, Mudala proposes a hybrid model with regulatory oversight, ensuring credibility while balancing the benefits of decentralisation. Finally, Mudala's focus on the South African market addresses a regional need, offering a unique advantage within the blockchain-based carbon offset space.

⁷UCT Energy Research Center: <https://www.erc.uct.ac.za/>

5.5 Challenges of Introducing Blockchain in Carbon Credits Markets

The promise of blockchain-based carbon credit markets is undeniable. However, introducing this technology requires careful consideration of its inherent challenges. This section will discuss the key challenges of blockchain technology, e.g., scalability, privacy, legal ambiguities etc.

Energy Consumption Issue: The PoW consensus mechanism, commonly used in blockchains like Bitcoin, demands significant energy and computational resources (Mougayar 2016). This process involves solving complex puzzles, leading to high electricity consumption and contributing to the technology's carbon footprint (Nour et al. 2022). To address this concern, alternative consensus algorithms like PoS, Proof-of-Authority (PoA), and Practical Byzantine Fault Tolerance (pBFT) offer significantly lower energy requirements (Vilkov and Tian 2023). For example, Hyperledger Fabric and Corda leverage these more efficient algorithms. Mudala leverages the Algorand blockchain, which utilises a PoS mechanism. This choice eliminates the high energy demand of PoW systems like Bitcoin, making Algorand ideal for environmentally focused applications like carbon credit marketplaces. Mudala's commitment to sustainability is directly reflected in its selection of blockchain technology.

Privacy : The inherent transparency of public blockchains, where transaction data is openly accessible, can raise concerns about revealing sensitive information in carbon credit markets (Nour et al. 2022; Wu et al. 2022). For instance, while Algorand offers the benefits of a permissionless, decentralised public blockchain, everyone can freely view transactions on the network. Mudala addresses this challenge by taking a privacy-focused approach. Transaction visibility is restricted to authorised participants within the platform. This design carefully balances the need for transparency with the protection of sensitive data.

Security Risks: While blockchain offers many benefits, potential vulnerabilities to cyberattacks remain a concern (Vilkov and Tian 2023). In certain scenarios, attackers could attempt to corrupt or change transaction records if they gain control of a majority of the network power – commonly called a '51% attack' (Nour et al. 2022). This highlights the significance of blockchain security design.

Mudala leverages the Algorand blockchain, which employs a secure PoS consensus mechanism. Algorand's design fundamentally mitigates 51% of attacks by preventing forks – situations where the blockchain splits into competing chains. This ensures only one valid block is finalised per round and allows transactions to be confirmed in under five seconds. Algorand's efficiency and fork resistance directly contribute to its enhanced

security.

Interoperability risks : Integrating blockchain with existing systems can be challenging due to compatibility issues. Standardising protocols and frameworks are crucial for achieving seamless interoperability and enabling diverse systems to work together effectively.

The Latency and Low Throughput Issue: Blockchain networks often face scalability limitations, leading to transaction processing delays. Increasing transaction throughput and reducing latency are vital goals to address these bottlenecks. Researchers are actively exploring innovative solutions like layer two scaling techniques. Additionally, hybrid web applications that combine blockchain security with traditional databases' speed offer a promising approach (Xu et al. 2016).

Mudala tackles scalability by combining blockchain technology with an off-chain database. This design enhances transaction processing speed and data storage capacity, improving scalability and reducing latency.

Legal and regulatory challenges: Uncertainty in legal and regulatory frameworks remains a significant challenge for blockchain applications. Current laws vary across jurisdictions, and transactions often involve nodes in multiple countries, making it unclear which laws apply. These inconsistencies result in complex, overlapping, and sometimes conflicting regulations for blockchain technology users. Disputes involving blockchain transactions further complicate matters, raising questions about jurisdiction and applicable legal principles. Adapting legal frameworks to address these challenges is crucial for widespread adoption and realising the full potential of blockchain solutions.

6. Conclusion and Future Work

6.1 Summary of the Main Findings

This study designs and implements Mudala, a carbon credits exchange platform built on the Algorand blockchain. Mudala facilitates the transparent and efficient creation and exchange of carbon credit tokens, which is crucial in reducing carbon emissions. Sellers initiate credit requests; regulators verify and release tokens based on certificates, as well as mint tokens. Sellers then proceed to sell credits and receive Algos, while buyers purchase credits to offset emissions. Aligned with the Paris Agreement's call for secure digital infrastructure, Mudala offers a solution for data integrity and accurate emission tracking.

We employ a blockchain suitability workflow using eight key criteria, including overall applicability, technical performance requirements, and governance and data access. This analysis confirms Mudala's suitability for a carbon market. Our proof-of-concept successfully addresses the research questions and objectives, showcasing a secure digital infrastructure aligned with the Paris Agreement's goals for data integrity and accurate emission tracking. Mudala's decentralised architecture guarantees finite and accurate carbon credit issuance, eliminating double spending and promoting trust through a clear, traceable credit life cycle. Secure and verified transactions on the Algorand blockchain ensure genuine emissions reduction and eliminate double-spending. Mudala reduces reliance on intermediaries and lowers transaction costs, encouraging wider participation and addressing wealth concentration issues. Neutral third-party validators enhance marketplace credibility and overcome conflicts of interest.

While the blockchain assessment confirms Mudala's technological feasibility, challenges remain, including energy consumption, privacy concerns, security risks, latency, and legal and regulatory issues. Despite these challenges, Mudala's features demonstrate significant potential in addressing climate change, exceeding the capabilities of traditional trading systems in terms of transparency, inclusivity, and sustainability.

6.2 Limitations and Future Directions

While this study demonstrates Mudala's potential, there are several limitations that require further investigation:

(i) Developed for the South African market, Mudala requires testing and analysis in other contexts to assess its generalisability for global carbon markets.

(ii) Implementing a comprehensive pricing model that factors in relevant market variables would enhance financial clarity and efficiency.

(iii) Expanding beyond the current model, where one regulator both certifies projects and manages token minting and allocation, would strengthen decentralisation and trust.

(iv) Replacing the centralised liquidity pool with smart contracts that directly match buyers and sellers would create a more seamless and efficient exchange process.

(v) Mudala currently allows users to manually input the number of tokens they wish to trade, assuming they are aware of their carbon emissions and the amount of CO₂ they need to offset. However, this approach introduces risks of user errors or manipulation, particularly for projects outside regulated industries. Additionally, the platform lacks automated verification tools to ensure the accuracy of this data. Integrating a system that automatically calculates the number of tokens required based on actual emissions data, verified by third-party independent auditors, would improve accuracy, control, and data integrity.

(vi) Collecting real-world data on user engagement, project participation, and user feedback is essential for validating Mudala's long-term effectiveness and sustainability.

Mudala's future directions focus on several key areas. First, the platform plans to implement automated order matching and refine the pricing model. Second, it aims to integrate carbon footprint calculators and third-party verification tools to ensure emissions are quantified accurately. These tools would allow users to input emissions data, and the system would automatically convert this data into the equivalent number of tokens required for offsetting. Third-party verification by accredited independent auditors would be used to ensure that data is trustworthy and that the projects meet their carbon reduction claims.

Future developments will also prioritise integrating Mudala with various carbon credit exchanges to address the challenge of double counting across platforms. By leveraging cross-chain interoperability and standardised carbon credit tracking mechanisms, Mudala can maintain transparency as the market grows more complex and interconnected. Collaboration with industry stakeholders to establish standardised carbon credit valuation methods will facilitate streamlined processes, broader participation, and more efficient resource allocation.

It is important to note that this research does not address the regulatory considerations surrounding such exchanges in a South African context, presenting another avenue for future exploration.

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A. Carbon Pricing Mechanisms in Different Regions

This table summarises carbon prices across different regions. Prices fluctuate annually, and new pricing mechanisms are regularly introduced. For the most up-to-date information, please visit the International Carbon Action Partnership (ICAP): icapcarbonaction.com

Table A.1: Carbon Pricing Mechanisms in Different Regions

Region	Country	Carbon Pricing Mechanism	Coverage	Price (tCO ₂ e)
Asia	China	ETS	30%	\$17
Asia	Kazakhstan	ETS	43%	\$1
Asia	South Korea	ETS	74%	\$17
Asia	Japan	Carbon Tax	75%	\$3
Europe	EU	ETS	39%	
Europe	Germany	ETS		
Europe	Poland	Carbon Tax	0.04%	\$0.08
Europe	Austria	ETS		
Europe	Sweden	ETS	40%	\$137
Europe	Finland	ETS	36%	\$72.8
Europe	Denmark	Carbon Tax		\$18
Europe	France	Carbon Tax		\$52
Europe	Spain	Carbon Tax		
Europe	Ireland	Carbon Tax		
Europe	Iceland	Carbon Tax	55%	\$35
Europe	Norway	Carbon Price		\$53
Europe	UK	ETS		
Europe	UK	Carbon Tax	23%	\$25
North America	Canada	Federal ETS	9%	\$32
North America	Canada	Carbon Tax	22%	
North America	Alberta	ETS	56%	
North America	British Columbia	ETS	78%	\$36
North America	Saskatchewan	ETS	11%	
North America	Quebec	ETS	78%	\$18
North America	US	ETS	80%	\$18
North America	US	ETS	16%	\$6.5
South America	Mexico	Carbon Tax	23%	\$3
South America	Mexico	ETS	40%	

Source: [Deidda et al. \(2022\)](#)

B. Mudala Implementation

This appendix provides screenshots showcasing Mudala's user interface. It features the landing page, registration process, authentication steps, and the use of Pera Wallet for purchasing or selling carbon credits.

B.1 Mudala Features

The web application features four main pages that users interact with: Home, Market, Validator, and Member Page. Navigation between these pages is handled by a side navigation bar. See screenshots below for a summary of Mudala features:

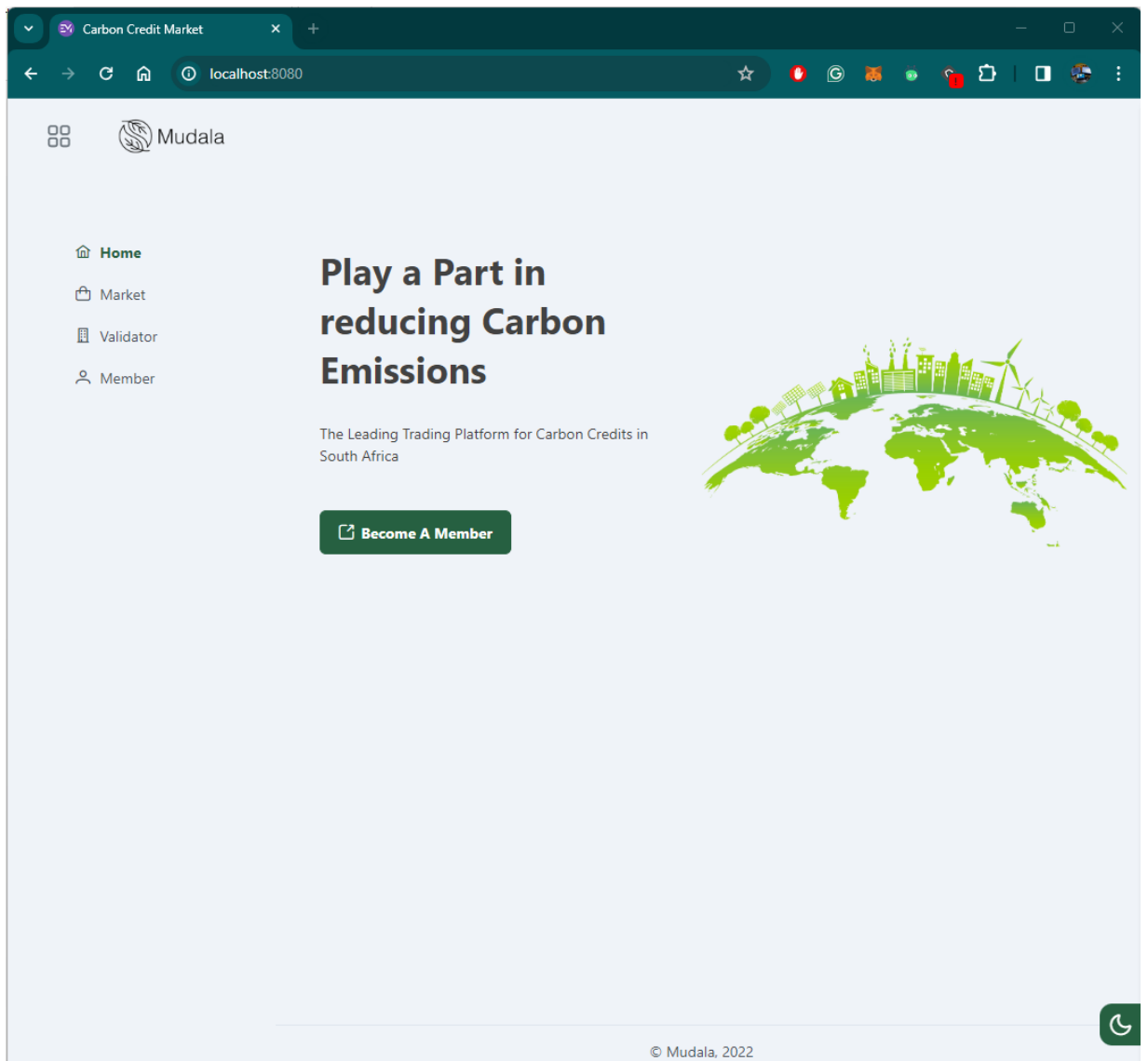


Figure B.1: Members can register on the platform through the landing page by pressing the “become a member” button.

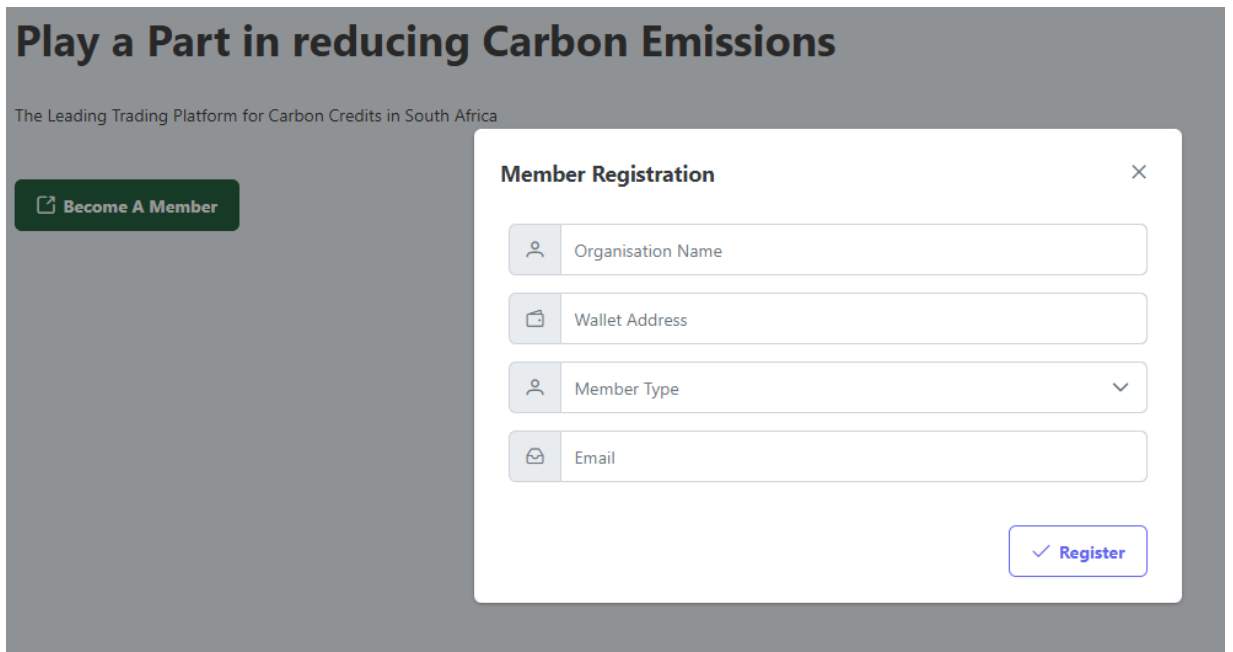


Figure B.2: As members register, they fill in their details, including Organization Name, Wallet Address, and Email Address, and choose the account type (buyer or seller) they wish to hold on the platform.

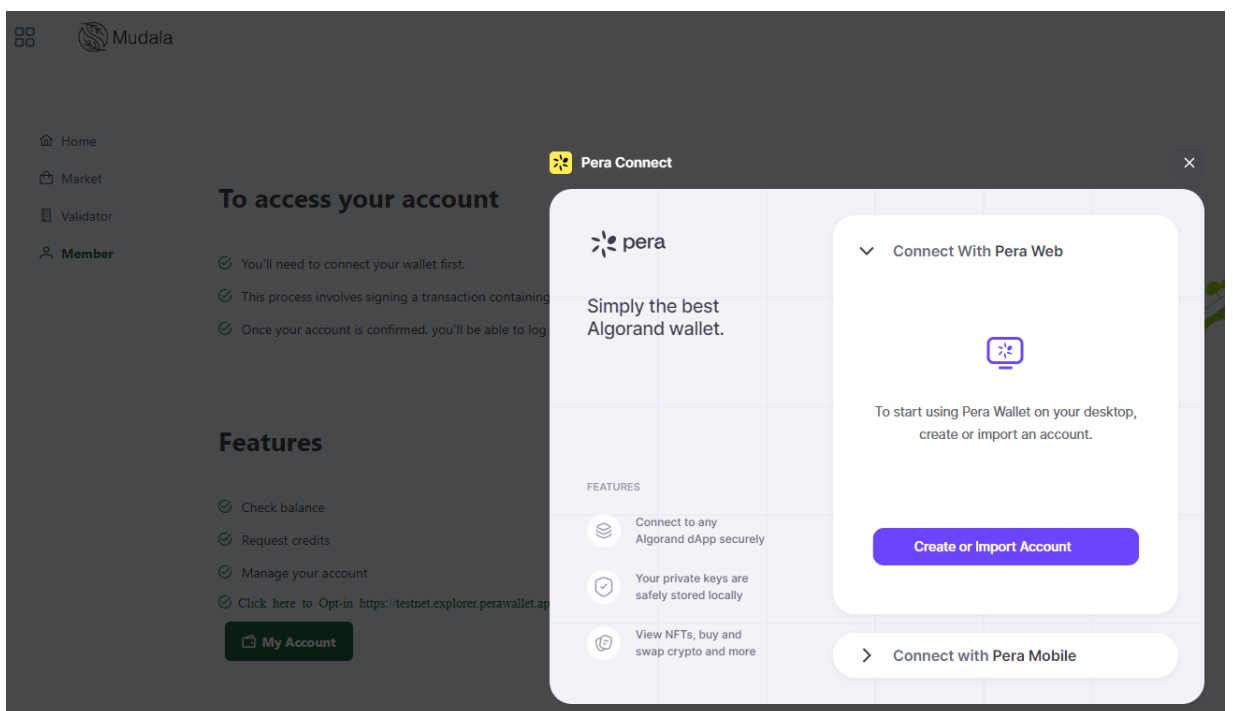


Figure B.3: To access your account, connect your wallet by signing a transaction with zero algos to authenticate your account, and once confirmed, you can log in and utilise our services.

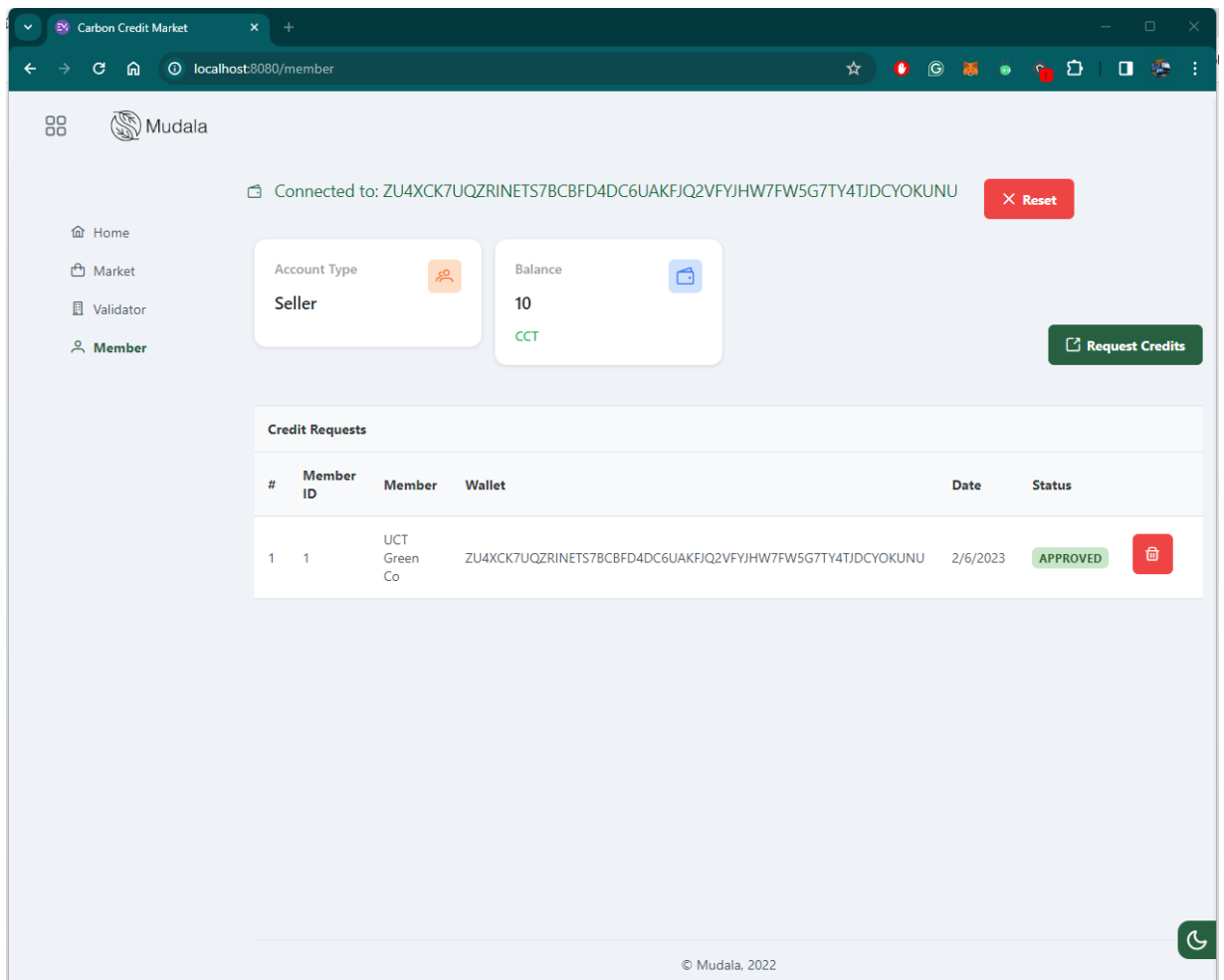


Figure B.4: If the member is confirmed as a seller, the page will refresh to display their details (token balance, credit request history). Sellers with no pending requests will also have the option to request additional tokens from the regulator.

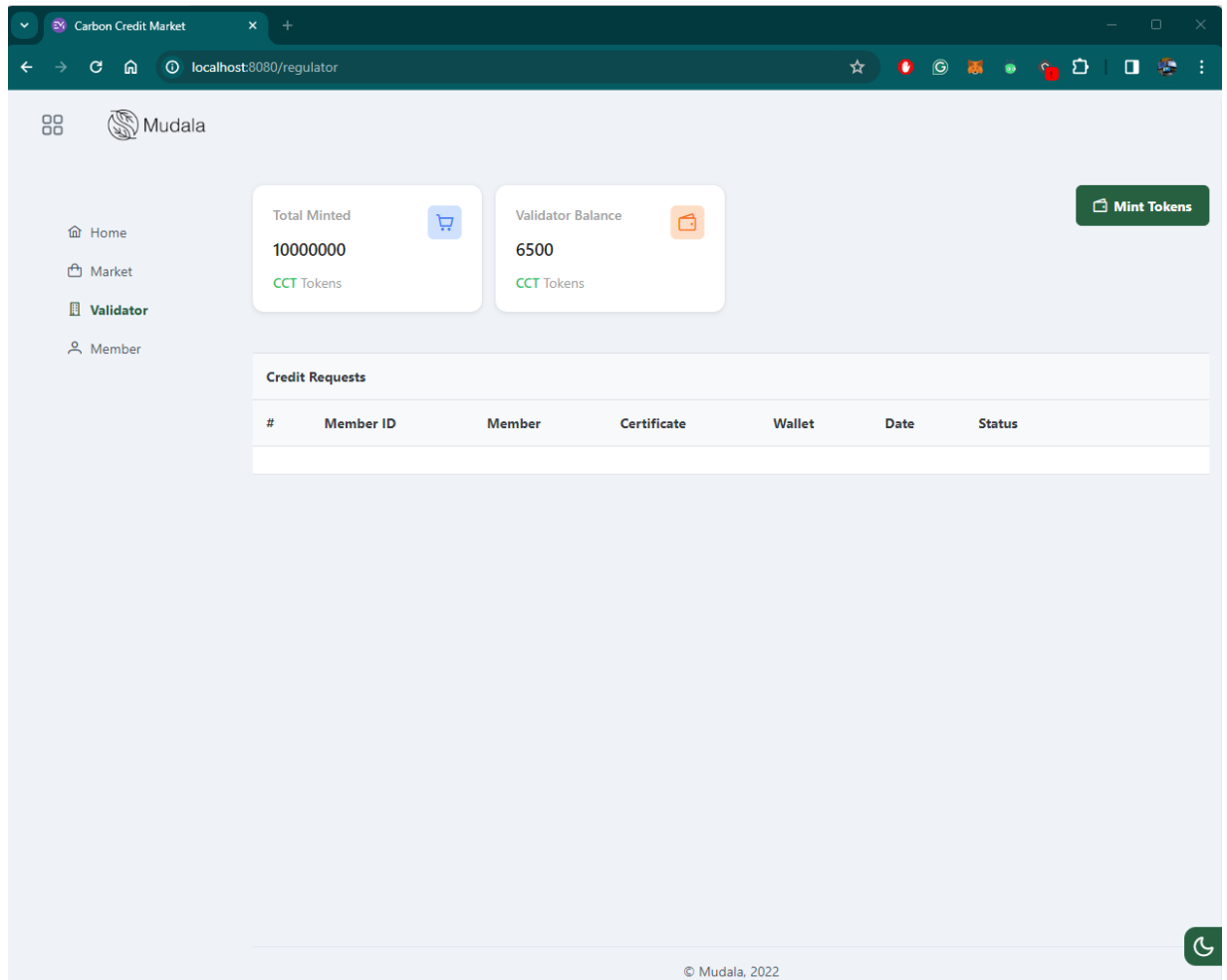


Figure B.5: The validator page provides a centralised view of pending seller token requests, allowing validators to approve or decline them. Additionally, validators can mint new tokens if reserves are low and view key metrics like available tokens and total tokens minted.

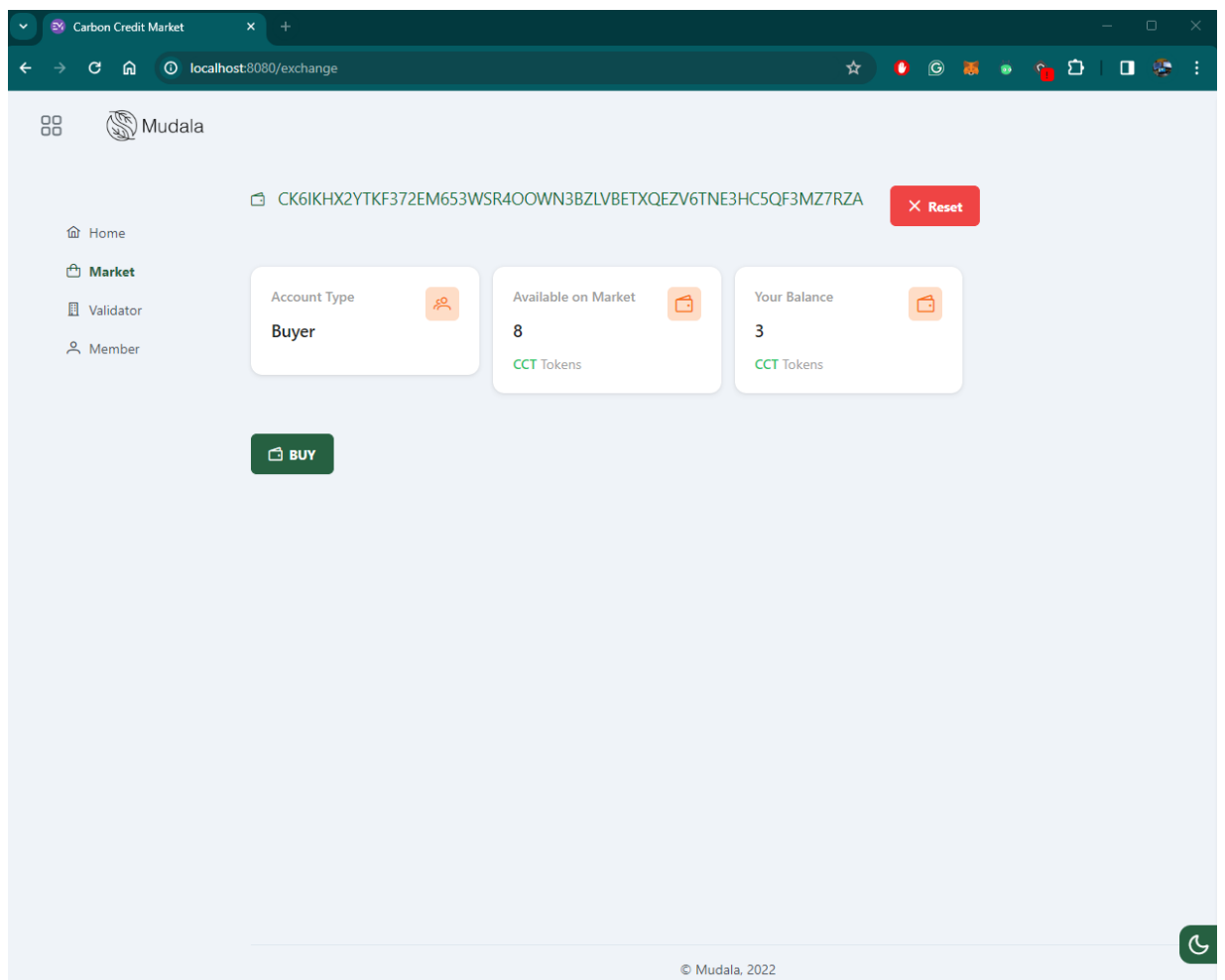


Figure B.6: If the account number is linked to a buyer membership in the SQLite database (confirming buyer status), the market page refreshes to display the dedicated buyer interface.

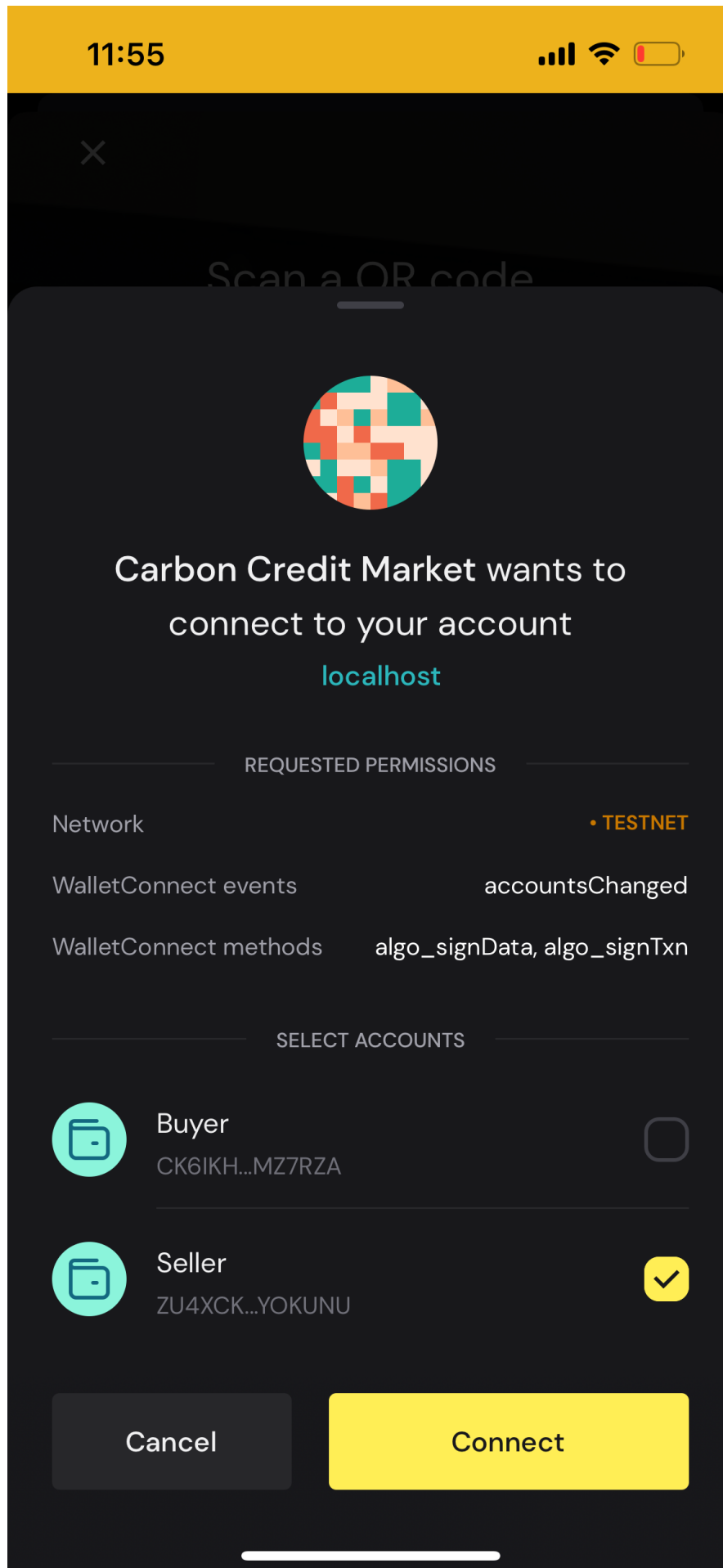


Figure B.7: Upon clicking the 'Connect' button, users can select the desired account to connect within their Pera Wallet.

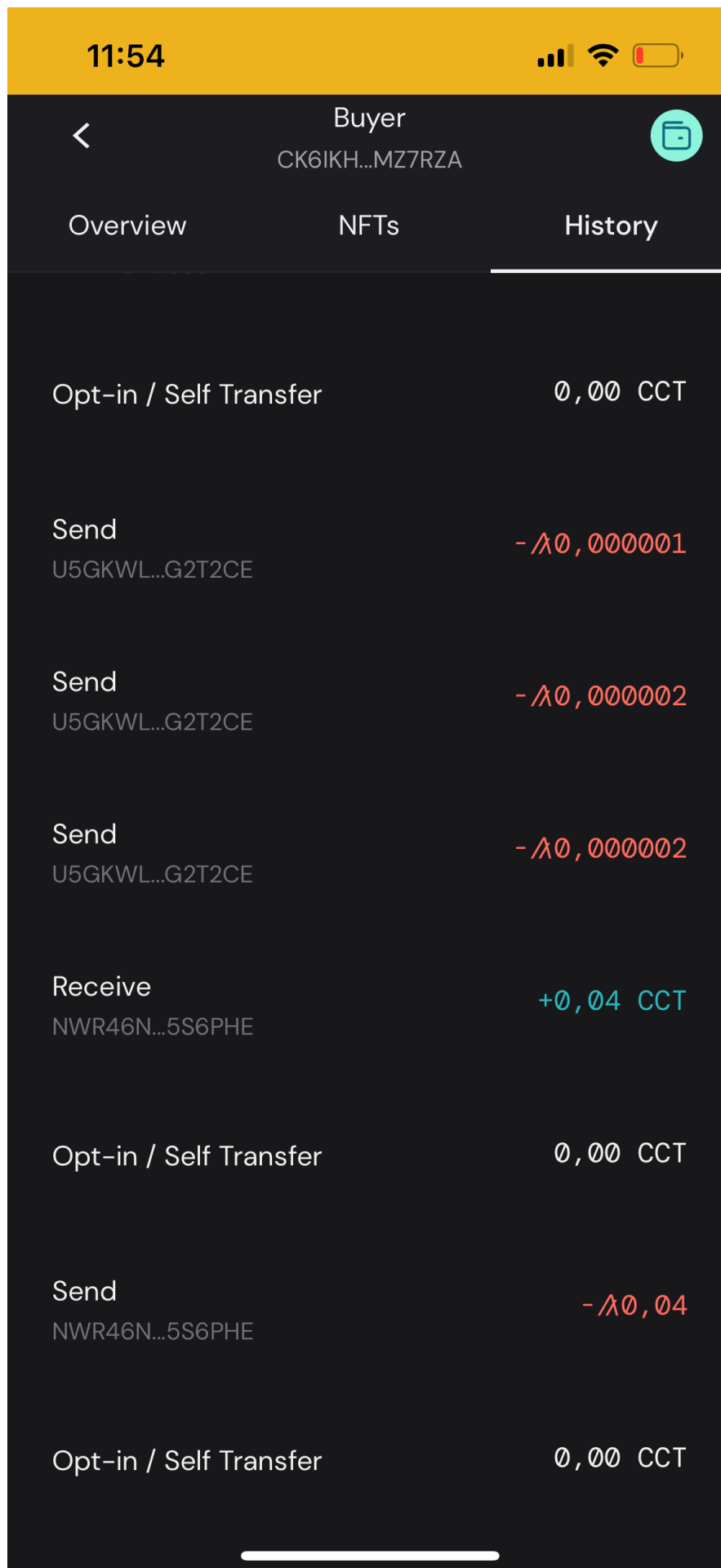


Figure B.8: This page displays your Pera Wallet transaction history as a buyer.

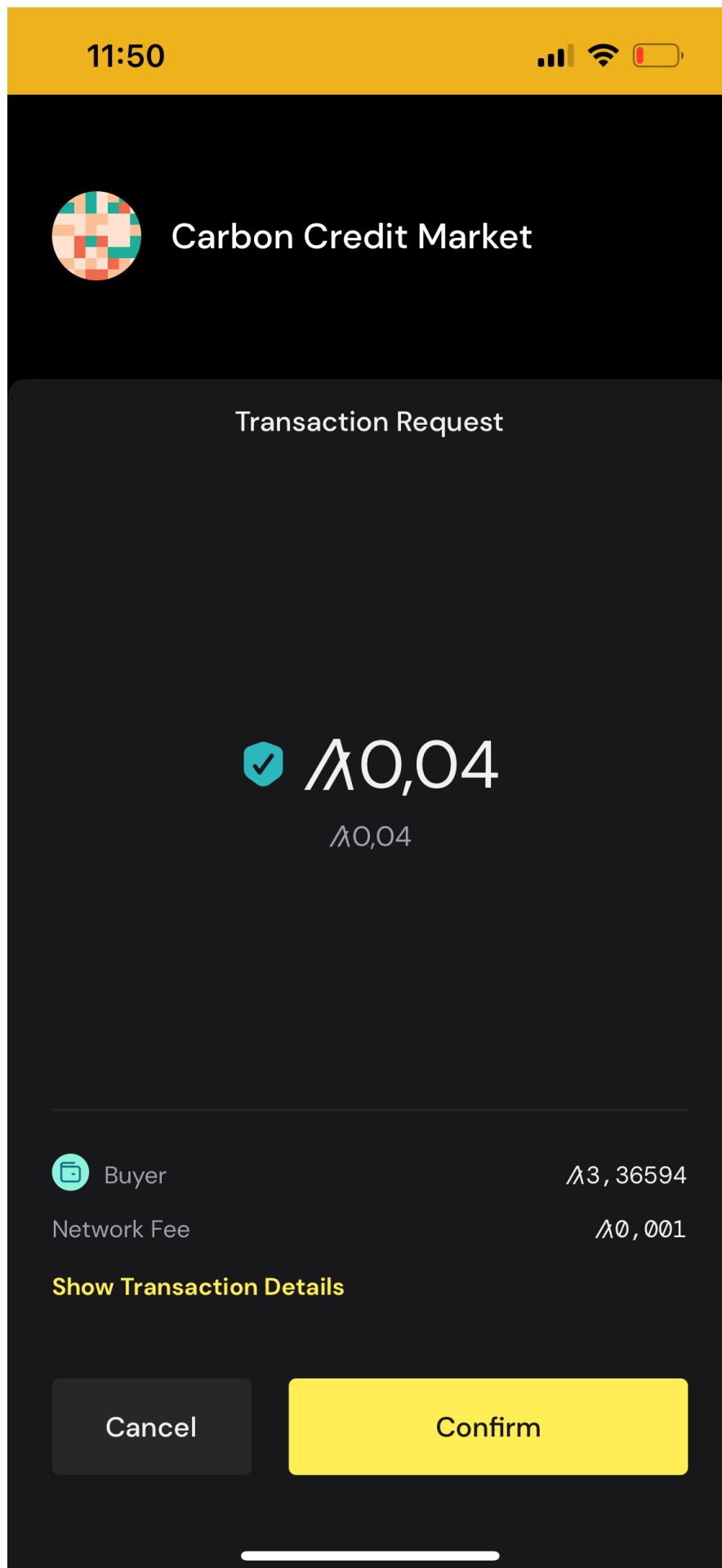


Figure B.9: This page provides an example of the transaction confirmation and signing process within Pera Wallet.

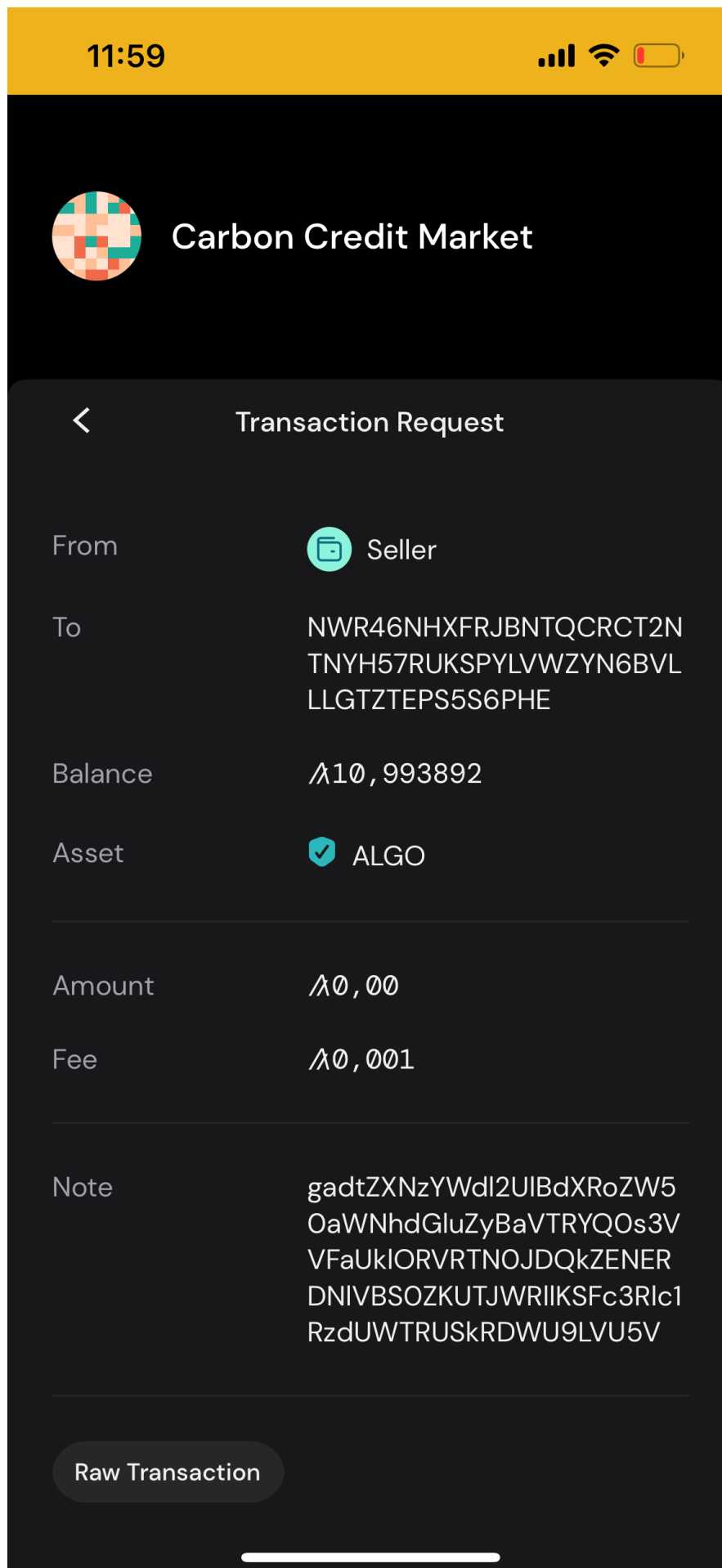


Figure B.10: This page displays the raw transaction details (including the amount, sender, fee, and any notes) before signing.

C. Mudala Source Code, Deployment, and Tools

This appendix provides detailed information on the source code, deployment, and supplemental technologies used in the development of Mudala.

C.1 Code

Mudala Source Code: <https://github.com/lisonyandu/mudala-project/tree/dev>

C.2 Deployment

Deployed Carbon Credit Token: <https://testnet.explorer.perawallet.app/asset/212175420/>

C.2.1 Accounts

- **Regulator Account:** This account is responsible for creating (minting) new carbon credits tokens and managing the overall supply based on verified carbon offset projects.
- **Reserve Account:** This account securely stores carbon tokens held in reserve, ensuring they back the tokens circulating on the exchange.
- **Market Account:** This account facilitates the buying and selling of carbon tokens within the Mudala exchange

C.2.2 Frontend and Backend

User Interface: mudala-carbon-exchange.onrender.com

C.3 Tools and Services

- **Pera Wallet:** Pera Wallet is a cryptocurrency wallet used to interact with the Algorand blockchain. It facilitates transactions and holds Algorand-based assets.
- **Render:** Render is a cloud application platform that streamlines hosting for web applications and services.

- **Algorand API:** The Algorand API provided by Nodely allows developers to interact with the Algorand blockchain.
- **Algorand JavaScript SDK:** The Algorand JavaScript SDK is a collection of tools and libraries designed to make it easier for developers to build applications that interact with the Algorand blockchain using JavaScript or TypeScript.