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ΜΗΧΑΝΙΚΩΝ & ΜΗΧΑΝΙΚΩΝ
ΥΠΟΛΟΓΙΣΤΩΝ

Βελτιστοποίηση Εικονικών Συμφωνιών Αγοράς Ισχύος (PPAs) χρησιμοποιώντας το Δίκτυο Optimistic Ethereum Blockchain

Σχεδιασμός, ανάπτυξη και εφαρμογή έξυπνων συμβολαίων ειδικά προσαρμοσμένων στο κλείσιμο Συμφωνιών Αγοράς Ισχύος (PPA)

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

ΧΡΗΣΤΟΣ ΡΟΥΜΕΛΙΩΤΗΣ

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HELLENIC DEMOCRACY
UNIVERSITY OF WESTERN
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FUCULTY OF ENGINEERING
DEPARTMENT OF ELECTRICAL &
COMPUTER ENGINEERING

Optimizing Virtual Power Purchase Agreements (PPAs) Using Optimistic Ethereum Blockchain Network

Design, development, and implementation of smart contracts specifically tailored for closing Power Purchase Agreements (PPA)

THESIS

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Kozani, Greece, October 20, 2024

ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
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ΔΗΛΩΣΗ ΜΗ ΛΟΓΟΚΛΟΠΗΣ ΚΑΙ ΑΝΑΛΗΨΗΣ ΠΡΟΣΩΠΙΚΗΣ ΕΥΘΥΝΗΣ

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Περίληψη

Σε αυτήν τη διπλωματική εργασία, ο κύριος σκοπός μας είναι να αποδείξουμε πώς η τεχνολογία blockchain μπορεί να εξαλείψει την ανάγκη για μεσάζοντες στις συναλλαγές ενέργειας, ειδικά στον τομέα της ανανεώσιμης ενέργειας. Παρόλο που πολλές χώρες έχουν τη δυνατότητα να παράγουν σημαντικές ποσότητες πράσινης ενέργειας, οι επιχειρήσεις αντιμετωπίζουν περιορισμένες ευκαιρίες για να επωφεληθούν άμεσα από αυτή την παραγωγή. Το τρέχον σύστημα περιλαμβάνει διάφορα επίπεδα μεσαζόντων, τα οποία όχι μόνο αυξάνουν το κόστος συναλλαγών, αλλά επίσης προκαλούν καθυστερήσεις και αναποτελεσματικότητα στην αγορά.

Χρησιμοποιώντας τις αρχές της αποκέντρωσης και της αυτοματοποίησης, το blockchain επιτρέπει πιο άμεσες, ασφαλείς και διαφανείς συναλλαγές μεταξύ των παραγωγών ενέργειας και των αγοραστών. Η πλατφόρμα μας στοχεύει στην απλοποίηση της διαδικασίας εμπορίας ενέργειας, επιτρέποντας στα μέρη να συμμετέχουν σε Εικονικές Συμβάσεις Αγοράς Ισχύος (VPPAs) χωρίς την ανάγκη μεσαζόντων, μειώνοντας έτσι τα κόστη και επιταχύνοντας τη διαδικασία συναλλαγής. Αυτό είναι ιδιαίτερα σημαντικό για μικρότερους αγοραστές και πωλητές ενέργειας, που παραδοσιακά αποκλείονταν από τέτοιες αγορές λόγω υψηλών χρεώσεων και περίπλοκων συμβατικών δομών.

Επιπλέον, επιλέξαμε το Layer 2 δίκτυο του Optimistic Ethereum Blockchain ως βασικό δίκτυο blockchain για το έργο μας. Αυτή η επιλογή βασίστηκε στην επεκτασιμότητα, την ασφάλεια και τις πολύ χαμηλές χρεώσεις συναλλαγών σε σύγκριση με τα παραδοσιακά blockchain δίκτυα. Οι λύσεις Layer 2, όπως το Optimistic Ethereum, μας επιτρέπουν να διαχειριζόμαστε μεγάλο όγκο συναλλαγών με αποδοτικότητα κόστους, γεγονός που είναι καθοριστικής σημασίας για να δοθεί η δυνατότητα σε μικρότερους συμμετέχοντες να εμπλακούν στην εμπορία ενέργειας. Με αυτόν τον τρόπο, διασφαλίζουμε επίσης ότι η πλατφόρμα μας είναι προσβάσιμη σε ευρύτερο φάσμα επιχειρήσεων, συμβάλλοντας έτσι στη δημοκρατικοποίηση των ενεργειακών αγορών, ανατρέποντας το παραδοσιακό τοπίο εμπορίας ενέργειας, προωθώντας ένα πιο ανοιχτό, αποκεντρωμένο και οικονομικά αποδοτικό περιβάλλον για συναλλαγές ανανεώσιμης ενέργειας, ενώ ταυτόχρονα ανοίγει το δρόμο για περισσότερες επιχειρήσεις να συμμετάσχουν στη μετάβαση προς την πράσινη ενέργεια.

Λέξεις Κλειδιά: Πράσινη Ενέργεια, Blockchain, Συμβάσεις Ισχύος

Abstract

In this thesis, our primary objective is to demonstrate how blockchain technology can eliminate the need for intermediaries in energy trading, particularly in the renewable energy sector. Many countries, despite having the potential to produce large amounts of green energy, offer limited opportunities for businesses to directly benefit from this production. The current system often involves multiple layers of intermediaries, which not only add to transaction costs but also create delays and inefficiencies in the market. By leveraging the principles of decentralization and automation, blockchain enables more direct, secure, and transparent transactions between energy producers and buyers. Our platform seeks to simplify the trading process by allowing these parties to engage in Virtual Power Purchase Agreements (VPPAs) without the need for intermediaries, thus reducing costs and speeding up the transaction lifecycle. This is especially relevant for smaller energy buyers and sellers who have traditionally been excluded from such markets due to high transaction fees and complex contract structures.

Moreover, we selected the Layer 2 Optimistic Ethereum blockchain as the foundational network for our project. This decision was driven by its scalability, security, and significantly lower transaction fees compared to traditional blockchain networks. Layer 2 solutions like Optimistic Ethereum allow us to handle a high volume of transactions while maintaining cost-efficiency, which is crucial for enabling smaller market participants to engage in energy trading. By doing so, we also ensure that our platform is accessible to a wider range of users, contributing to the democratization of energy markets, disrupting the traditional energy trading landscape, fostering a more open, decentralized, and cost-efficient environment for renewable energy transactions, while also paving the way for more businesses to participate in the green energy transition.

Keywords: Green energy, Blockchain, Power Purchase Agreements

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I would like to express my deepest gratitude to my professor, Vasilis Lazaridis, who always believed in me and supported me throughout the development of this thesis. His guidance and trust were a source of inspiration and motivation, helping me complete this work.

I cannot forget to thank my family, especially my parents, who stood by my side through every step of my journey, with endless patience and understanding. My brother, with his unwavering support, was always there when I needed him the most.

I would also like to thank my friends and colleagues for their support, which I deeply appreciated during this journey. Without their encouragement and constructive feedback, our work and goals would not have been achievable.

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Motivation

The global energy sector is undergoing a profound transformation driven by the urgency to transition towards sustainable and renewable energy sources. Although most countries have the right conditions for renewable energy generation, businesses have had limited opportunities to benefit from clean energy. Central to this shift is the utilization of Power Purchase Agreements (PPAs), which have historically played a crucial role in promoting renewable energy and managing the transition from regulated to competitive electricity markets. However, traditional PPAs are often complex, time-consuming, and expensive, creating barriers to entry for smaller energy producers and buyers. In countries such as Oman and Saudi Arabia, the transition to a market-based energy system has involved significant restructuring, with PPAs being key instruments in this evolution. Yet, the financial challenges faced by state-owned utilities highlight the need for more efficient and flexible contracting mechanisms to support the growing demand for renewable energy investment [1].

Virtual Power Purchase Agreements (VPPAs) have emerged as a pivotal solution in this landscape, enabling companies to financially hedge against market fluctuations and secure green energy without taking physical delivery. Despite their advantages, VPPAs are often hindered by complex, lengthy processes and high transaction costs, which can reach up to $1 million and extend lead times to 12-18 months [2]. This has limited their accessibility, predominantly benefiting large corporations with substantial legal and financial resources, while excluding smaller entities that also seek to participate in green energy procurement [3].

To address these inefficiencies, blockchain technology, specifically Layer-2 solutions such as Optimistic Ethereum, presents a transformative opportunity. Blockchain's decentralized nature, coupled with its ability to automate processes through smart contracts, offers the potential to streamline VPPAs, significantly reducing processing times. Blockchain technology has the potential to enhance the security and transparency of energy transactions, thereby addressing existing bottlenecks in the VPPA market [4]. The integration of smart contracts on blockchain platforms like Ethereum allows the execution of predefined agreements between energy producers and buyers in a decentralized, immutable, and automated manner, which reduces the need for third-party intermediaries [5].

The motivation for this thesis lies in addressing the existing bottlenecks in the VPPA market through innovative blockchain solutions. By integrating Optimistic Ethereum, we seek to demonstrate how VPPAs can be made more accessible, fast and secure, ultimately supporting the financing and operation of renewable energy projects such as photovoltaic and wind parks. Our approach aims to create a scalable, automated platform that simplifies the matching of green energy producers with buyers, ensuring that the terms of the agreement are immutably recorded and enforced via blockchain technology. Furthermore, the extension possibilities of this approach include enhancing cross-border energy trading and expanding the market reach of renewable energy investments. This work contributes to the broader goals of energy market liberalization and sustainability, offering a blueprint for the future of green energy procurement in a digitally transformed landscape.

Chapter 1: Scope

1.1 Scope

We examine the potential of blockchain technology, specifically the Optimistic Ethereum Layer-2 solution, to optimize VPPAs and mini-energy trading processes. Our primary focus is on addressing key quality aspects such as scalability, transparency, and security within blockchain-based energy trading systems.

For scalability, we concentrate on evaluating how Optimistic Ethereum can overcome the limitations of traditional blockchain networks. By leveraging Layer-2 scaling solutions, we aim to enhance PPA' s creation process throughput and secure funds and/or potential buyers, making PPAs more accessible to a broader range of participants, including smaller energy buyers and producers.

In terms of security, we limit our investigation to industry best practices and widely recognized standards for smart contract development. We will implement and assess security measures within the context of the Optimistic Ethereum environment, including formal verification techniques and automated security testing tools. Our evaluation will focus on identifying vulnerabilities specific to such a VPPA platform and energy trading use cases.

The technical implementation involves developing a decentralized app (DApp) that facilitates the publication of VPPAs and the execution of mini-energy trading on a marketplace-type platform. This DApp will be designed to create and close a VPPA and buy energy through it, transparently and securely, utilizing Solidity for smart contract development. We will employ tools such as the Truffle Framework for streamlining the development and deployment processes, along with React JS for UI development.

Additionally, the scope includes exploring the integration of green certifications within the VPPA platform. By incorporating verifiable green certifications on the blockchain, we aim to enhance the credibility and market appeal of VPPAs, ensuring that the energy procured meets sustainability criteria and is transparently tracked from production to consumption.

The practical components of this thesis will involve a proof-of-concept implementation that demonstrates the feasibility of our proposed models. We will assess the performance, scalability, and security of the developed system through a series of experiments, highlighting the potential for Optimistic Ethereum to change the way VPPAs are managed and executed in the green energy sector.

1.2 Research Topics

In this thesis, we focus on exploring several key research areas that aim to advance the understanding and application of blockchain technology in the energy sector:

1. **Scalability of Blockchain Architectures**: Traditional blockchain platforms, like Ethereum, are constrained by limited transaction throughput, leading to network congestion and inflated fees. This thesis will examine how Layer-2 solutions, particularly Optimistic Ethereum, can significantly improve scalability while adhering to decentralization and security principles. This investigation will include an analysis of the technical structure of Optimistic Ethereum, its consensus protocols, and how it effectively manages the trade-offs between scalability, cost, and decentralization.
2. **Modeling a Decentralized VPPA and Mini-Energy Trading System**: Our work will model a decentralized system for publishing VPPAs and conducting mini-energy trades within a marketplace ecosystem, built on the Optimistic Ethereum blockchain. The system must efficiently track and manage energy transactions between buyers and sellers, maintaining transparency and security by leveraging blockchain’s immutable ledger. The system will also need to ensure accuracy in energy accounting for each buyer and seller based on pre-agreed models.
3. **Enhancing Smart Contract Security and Streamlining Auditing**: A key focus of the thesis will be identifying ways to improve smart contract security, a critical aspect of decentralized systems. We will investigate methods to streamline the auditing process to ensure contracts are secure without sacrificing development speed. This section will explore contemporary auditing techniques and tools while evaluating potential vulnerabilities that could compromise energy trading systems.
4. **Integration of Green Energy Certificates in Blockchain-Based PPA Platforms**: With increasing attention to sustainability, green energy certificates are essential for verifying the provenance of renewable energy. This thesis will explore how blockchain can be employed to integrate green certifications, such as Guarantees of Origin (GOs) in Europe, into the VPPA process. The use of blockchain for this purpose enhances transparency and trust in the energy market, ensuring that environmentally conscious buyers can confidently purchase renewable energy with verified credentials.

This study aims to show that through decentralized systems powered by blockchain technology, traditional energy trading intermediaries can be eliminated, resulting in more efficient and direct transactions between producers and consumers. Furthermore, by utilizing Optimistic Ethereum, we can demonstrate how scalable, secure, and cost-effective solutions can be implemented, providing a model for future applications in the energy sector.

1.3 Outline

This thesis is structured to investigate the use of blockchain technology, specifically Optimistic Ethereum, for optimizing VPPAs and creating an efficient energy trading system. In **Chapter 1**, we introduce the scope and key research topics, focusing on the potential of Layer-2 solutions to address scalability, transparency, and security issues in decentralized energy markets. **Chapter 2** covers the theoretical foundations of PPAs and VPPAs, including an overview of energy markets and the role of blockchain in streamlining these contracts. This chapter also highlights existing models and frameworks for energy trading.

In **Chapter 3**, we delve into Optimistic Ethereum as a Layer-2 solution, explaining its structure, scalability benefits, Optimistic Virtual Machine (OVM) and how it improves upon traditional blockchain models. **Chapter 4** describes the conceptual approach and the technical implementation of a DApp to facilitate VPPA creation and energy trading. **Chapter 5**discusses the smart contracts used, with a particular focus on the use of ERC-1155 and ERC-1888 standards to manage energy certificates and automate trading. Finally, **Chapter 6** evaluates the system's performance and scalability through testing, and **Chapter 7** concludes by summarizing the results and offering insights for future development and improvements in the blockchain-enabled energy market.

1.4 Full Development

We provide key code snippets throughout the document when necessary to illustrate specific concepts or functionalities of the smart contracts. For a comprehensive view, the full code is available upon request. This includes all smart contract implementations, test cases, and deployment scripts used in the thesis.

Chapter 2: Theoretical Part

2.1 Power Purchase Agreements (PPAs)

A PPA, also known as an electricity power agreement, is a legally binding contract between two entities. One entity is responsible for generating electricity (referred to as the seller or developer), while the other entity intends to buy electricity (referred to as the buyer). The PPA encompasses all the contractual aspects related to the sale of power, such as fixed or indexed pricing, as well as the scheduling of commercial operation and electricity delivery. It also includes provisions for penalties in case of under delivery, payment terms, and termination conditions. A PPA is a crucial contract that outlines the income and creditworthiness of a power generation project, making it a vital component of project funding [6].

This contrasts with the conventional method of directly purchasing electricity from authorized electricity providers, commonly referred to as utility (or wholesale) PPAs. PPA is a method of selecting a specific form of energy, such as renewable energy, in order to enhance the overall rating of a company's assets and reduce its carbon footprint [7]. By entering into a PPA with a solar or wind farm, a company can achieve its goal of increasing the percentage of renewables in its energy mix [8].

PPAs are utilized for power projects in situations where:

- To ensure the viability of the project, it is necessary to have guarantees regarding the quantities purchased and the price paid, as the projected revenues would otherwise be uncertain.
- The PPA offers protection against potential competition from cheaper or subsidized domestic or international sources, such as a neighboring power plant producing power at a lower cost.
- The project relies heavily on one or a few major customers who will be purchasing the majority of the product. For instance, a government entity responsible for providing public services may be procuring the electricity produced by a power generation facility [9]. The government will seek to ascertain the cost of its power and ensure that it has priority access to that power. The project business seeks assurance of consistent earnings, while the purchaser desires to ensure a reliable and uninterrupted supply.

Table 1: Key business models involving PPAs.

Key business models involving PPAs	Description
Wholesale PPA	The most basic form of a PPA is the "Wholesale model", in which the generator sells all the power it produces back to the grid. The majority

	of the renewable energy sources (RES) were deployed utilizing this framework, whereby licenses were auctioned to produce a specific quantity of energy in return for a predetermined tariff per megawatt-hour (MWh).
On-site PPA	Rather than selling all excess energy back to the grid, particularly from energy-intensive activities such as running company servers, they aim to increase the proportion of RES in their overall energy mix. They can achieve this by obtaining power directly from a generator and entering into a separate PPA to either sell the excess power produced or serve as a backup supplier if needed.
Sleeved off-site PPAs	In a Sleeved PPA, the corporate consumer sells all the power it generates to a licensed supplier, sometimes known as a balancing party. This arrangement is like a Back-to-Back PPA, where the electricity supplier purchases all the power acquired by the consumer. The consumer repurchases the electricity it consumes to accomplish the balancing function.
Synthetic PPA	A Synthetic PPA, also referred to as a "Virtual PPA," is a contractual arrangement in which a power generator obtains the market price for their electricity under the PPA, and the generator and consumer reconcile the difference between the market price and a predetermined fixed price. The virtual nature of electricity purchases in most Contract for Difference is due to the absence of physical acquisition of electricity.

As illustrated in Table 1, various business models involving Power Purchase Agreements (PPAs) exist to facilitate energy transactions. These include the **Wholesale PPA**, where the energy generator sells all produced power back to the grid at predetermined tariffs, and the **On-site PPA**, where companies seek to increase their renewable energy mix by obtaining power directly from a generator. The **Sleeved off-site PPA** involves selling generated power to a licensed supplier, while the **Synthetic PPA** focuses on reconciling the difference between the market and agreed-upon prices, often referred to as a 'Virtual PPA.' Each model caters to different business needs and operational structures in the energy market, enhancing both flexibility and market adaptability [10].

2.2 Virtual PPAs (vPPAs)

A VPPA is a multi-year bilateral renewable energy contract (It usually lasts about 8-20 years) sourced from a specific plant. Because of the structure of a VPPA, such deals are also known as “contracts for differences,” or “fixed-for-floating swaps,” since the buyer is effectively paying a fixed $/MWh rate and receiving a floating market $/MWh rate in return. It is only available in regions with a wholesale electricity market, and the seller does not physically deliver the energy to the customer. Instead, the energy produced by the plant is sold into the reference electricity market [11].

Under a VPPA, the customer does not physically receive the energy from the plant but continues to receive electricity from their existing supplier. The spot market price fluctuates and differs from the price agreed upon between the client and the seller in the VPPA. If the agreed VPPA price is lower than the market price, the client receives the difference from the seller based on the energy produced by the plant. Conversely, if the VPPA price is higher than the market price, the customer compensates the seller for the difference [12].

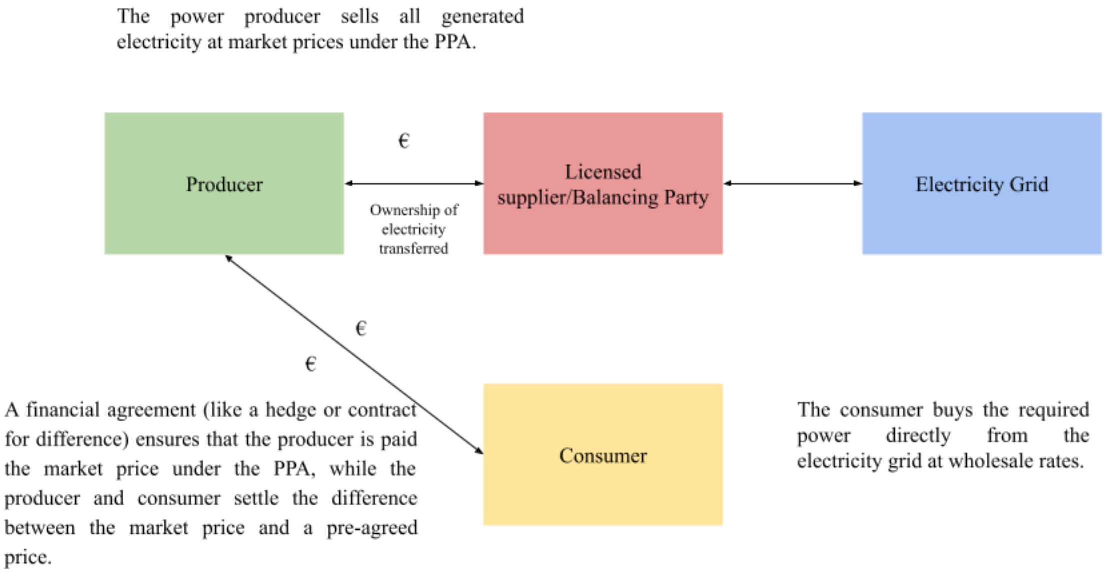


Figure 1: A visual representation of the energy and financial transactions between a power producer, supplier, grid, and corporate consumer under a PPA.

Additionally, the client receives green certificates, which guarantee the renewable origin of the energy purchased through the VPPA. These certificates are crucial for companies aiming to reduce their carbon footprint and enhance sustainability ratings [13]. VPPAs offer an optimal solution for companies with multiple locations, as they allow the client to maintain their current electricity supplier while meeting their renewable energy targets [14].

2.3 Energy Attribute Certificates (EACs)

Utilizing renewable energy is an important component of achieving a net zero transition. It decreases scope 2 emissions in accordance with the Greenhouse Gas (GHG) protocol, following both statutory regulation and voluntary reporting criteria. If an entity is unable to generate its own renewable energy due to laws or technical challenges, or if it is not accessible for purchase, acquiring EACs becomes a simple and environmentally-friendly option. Employing EACs is the sole reliable and provable method to assert renewable energy usage [15].

EACs are official documents that provide proof of the environmental attributes associated with the production of renewable energy. They were established with the purpose of monitoring the flow of electricity from its source to the end user. Electricity is an intangible entity that requires continuous maintenance on a grid. When electricity is purchased, the buyer is acquiring the entitlement to extract a specific quantity from the power grid. A tracking system is the sole means of linking the production and use of a particular MWh of electricity. The system records the EACs when electricity is added to the power grid [16].

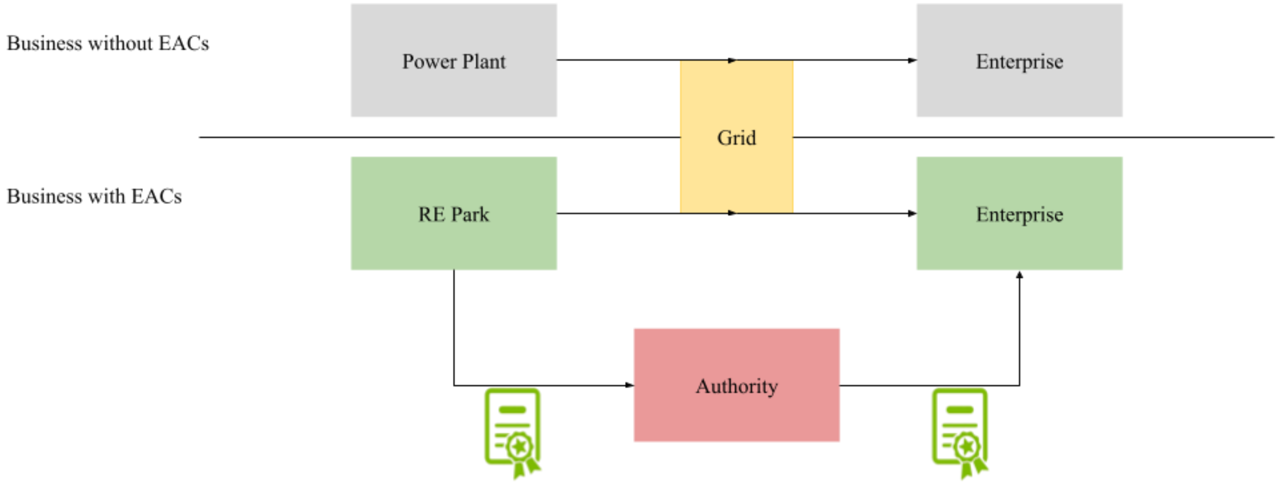


Figure 2: This diagram shows the transition of a business from non-renewable to renewable energy sources through EACs.

These unique characteristics can then be transferred to the consumer, who can make a reliable and verifiable statement that a specific sort of electricity has been consumed. All EAC monitoring systems share a common purpose: to monitor the characteristics of a particular MWh of energy as it moves from a producer to a consumer.

Globally, multiple EAC systems are in place to monitor the generation and consumption of renewable energy. The map provided displays the countries that are involved in the most prevalent schemes, as well as the boundaries of their respective markets. Every system functions according to its own set of regulations and has a specialised register system [15], [16]. The four primary geographical markets are:

- GOs are predominantly utilised in Europe. Every European country that is a member of the Association of Issuing Bodies (AIB) actively takes part in the European Energy Certificate System (EECS).
- Renewable Energy Certificates (RECs) are the prevailing system utilised in the majority of provinces in Canada and states in the United States.
- International Renewable Energy Certificates (iRECs) are used by many governments throughout the world to monitor and trace the use of renewable energy.

- National Country Systems: Numerous countries have established their own EAC programs. Some examples include:
- Poland's accreditation is granted by TGE, the registered commodity exchange in Poland, and its management is overseen by the Polish registry.
- Renewable Energy Guarantees of Origin (REGO) is the specific system employed in the United Kingdom.
- Tradeable Instruments for Global Renewables (TIGRs) are utilised by several countries, such as Singapore and Taiwan.
- Australia utilises Renewable Energy Target Certificates and Large-scale Generation Certificates to support its renewable energy goals.
- Japan utilises non-fossil certificates to facilitate its operations.
- South Africa utilises zaRECs, which stands for South African Renewable Energy Certificates.

Table 2.: Key benefits of EACs

Key Benefits of EACs	Description
Traceability	Each MWh of electricity is tracked meticulously from producer to consumer within national and international registries. The risk of double counting is eliminated as EACs are cancelled upon consumption, ensuring a reliable tracking process.
Cost Efficiency	EACs provide a cost-effective method of sourcing renewable electricity. They are relatively low-cost compared to other options for procuring renewable energy, making them accessible for a wide range of organizations.
Effectiveness	Procuring EACs is a simple and effective strategy for reducing scope 2 emissions. This makes them a practical choice for organizations aiming to meet their sustainability goals.
Transparency	EACs offer transparency by unbundling renewable energy consumption. They provide certificates that verify the consumption of renewable energy, along with information about the region and type of energy generation device. This documented evidence is valuable during audits and helps in maintaining regulatory compliance.
Adoption by Standards	EACs are recognized by international standards such as the Corporate Sustainability Reporting Directive (CSRD) and other climate certification programs. Their acceptance as a tool to reduce scope 2 emissions contributes to lowering an organization's overall carbon footprint.
Claims	Organizations that purchase EACs can make credible claims such as being "in line with RE100" or "100% Renewable." These claims enhance the organization's environmental credentials and support their commitment to sustainability.

An EAC can be supplied either bundled with the underlying power or as a standalone product. When the EAC and the underlying electricity are traded together in a contract, it is referred to as being 'bundled'. When each of them is traded in distinct contracts, it is referred to as 'unbundled'. Regardless of the scenario, the fundamental principles remain the same, resulting in two distinct product streams: 1. the electrical energy itself, and 2. the inherent characteristics, which are symbolised by an EAC. Both the utilisation of bundled and unbundled EACs are legitimate methods of using renewable energy [15], [16], [17].

2.4 Blockchain technology in optimizing vPPAs

Blockchain technology has the potential to significantly optimize VPPAs by enhancing transparency, security, and efficiency. Using a decentralized ledger, blockchain ensures that all transactions and contract details are immutable and tamper-proof, which fosters trust between energy producers and corporate consumers. This technology allows for real-time tracking (combined with equipment, IoT) of energy generation and consumption, ensuring that renewable energy claims are credible and transparent [18], [19]. Additionally, blockchain enables the use of smart contracts, which can automate transactions, reducing the risk of human error or fraud. The cryptographic features of blockchain further secure the data associated with VPPAs, protecting sensitive information from cyber threats, which is crucial given the financial and operational data involved**.** Moreover, blockchain streamlines the VPPA process by reducing the need for intermediaries, leading to cost savings and faster contract execution. The technology also supports the verification and tracking of EACs, ensuring that the energy sold under a VPPA is genuinely renewable and not subject to double counting. Blockchain's decentralized nature facilitates the seamless execution of VPPAs across different countries, making it particularly advantageous for multinational corporations looking to purchase renewable energy globally. Additionally, blockchain can support dynamic pricing models and peer-to-peer energy trading, allowing for more flexible and decentralized energy markets. This technological advancement ultimately contributes to the growth and adoption of renewable energy by making VPPAs more reliable and efficient [20], [21]**.**

2.5 Ethereum Request for Comments (ERC)

In Ethereum, **standards** refer to predefined rules and guidelines that ensure interoperability, security, and functionality within the Ethereum blockchain ecosystem. These standards are critical for creating and interacting with smart contracts, tokens, decentralized applications (dApps), and other blockchain-based systems. The **Ethereum Request for Comments (ERC)** process defines these standards, with various ERC proposals addressing different use cases [22], [23], [24], [25].

Key Ethereum Standards (ERCs):

- **ERC-20**: This is the most well-known and widely adopted standard for creating fungible tokens on Ethereum. Fungible tokens are identical and interchangeable with one another, like currencies. The ERC-20 standard defines six key functions that a token smart contract must implement, such as `transfer, balanceOf, and approve`.
- **ERC-721**: ERC-721 is a standard for **non-fungible tokens (NFTs)**, meaning each token is unique. This standard is widely used in applications such as digital collectibles (e.g., CryptoKitties) and assets that require unique ownership rights.
- **ERC-1155**: This is a **multi-token standard** that allows a single smart contract to manage both fungible and non-fungible tokens. It's more efficient than ERC-20 and ERC-721 for applications like gaming, where both token types (e.g., in-game currencies and unique items) are needed. ERC-1155 reduces the transaction and gas costs by enabling batch transfers of different tokens.
- **ERC-1888**: This is a relatively newer standard designed for **EACs**, a specific type of token representing environmental commodities like renewable energy credits. ERC-1888 facilitates the management, trade, and redemption of green energy certificates on the blockchain, making it highly relevant for energy markets and green energy certification projects.

How ERCs Work

- **ERC proposals** are typically initiated by developers who seek to address a specific problem or requirement in Ethereum's ecosystem.

- **ERC development** follows a structured process. Once an ERC is drafted, it is submitted for community review and can eventually be adopted as a standard after thorough vetting and feedback.
- **Adopted standards** become key components of Ethereum's ecosystem, allowing for the creation of interoperable contracts and applications that adhere to these well-defined rules.

Importance of Standards in Ethereum

- **Interoperability**: Standards like ERC-20 and ERC-721 enable tokens and contracts to work seamlessly across different decentralized applications.
- **Security**: Well-defined standards reduce the likelihood of errors and vulnerabilities by providing tested and widely understood guidelines for contract development.
- **Scalability and Efficiency**: Standards like ERC-1155 allow for more efficient operations, such as batch transfers, which reduces gas fees and improves transaction throughput.

2.6 Related Bibliography Work

Blockchain technology has gained significant traction in the energy sector, particularly for enabling decentralized and transparent energy trading mechanisms, facilitating the management of PPAs, and optimizing Virtual Power Plants (VPPs). The growing integration of blockchain into these systems offers solutions for improving scalability, security, and transparency, essential for evolving energy markets. This section reviews key research that contributes to the application of blockchain technology in optimizing PPAs and managing decentralized energy trading systems, especially within the context of VPPs and distributed energy resources (DERs).

The efficient management of PPAs has long posed challenges due to the complexity of contract conditions and the need for transparency. In [26] propose a novel approach for addressing these challenges by using blockchain technology to enhance the cost-efficiency of PPAs. Their work introduces a distributed system that automates data management and provides total traceability and integrity throughout the lifecycle of a PPA. The blockchain-based method ensures the consumer’s self-management capability and the guarantee of origin for renewable energy, which improves market confidence. The system outlined in the paper offers operational designs that integrate energy balance and cost formulas, proving that blockchain can streamline PPA management while enhancing data ownership and transparency. This research is foundational in demonstrating the potential of blockchain to reduce the administrative complexity and costs associated with PPAs while improving trust and reliability in energy transactions . The integration of peer-to-peer (P2P) energy trading mechanisms into VPPs through blockchain technology is an emerging field. In [27] developed a blockchain-based architecture for P2P energy trading within VPPs using Ethereum smart contracts. Their proposed system allows prosumers—who generate renewable energy from sources like solar and wind—to participate in auctions and trade surplus energy with other agents in the network. The smart contracts automate the bidding, withdrawal, and control mechanisms, ensuring transparency, security, and fairness in the trading process. A key advantage of using Ethereum’s public network is its adaptability and transparency, enabling real-time energy trading while addressing cost concerns and enhancing security. This work highlights the role of smart contracts in reducing operational costs and security risks through automated contract execution and auditing, which is crucial for decentralized energy trading systems .

The study by [28] further advances the understanding of blockchain's role in VPP operations. Their research emphasizes the importance of integrating blockchain to manage transactions and energy distribution within VPPs. By employing a continuous double auction mechanism, the authors demonstrate how blockchain can facilitate peer-to-peer transactions of distributed energy resources, promoting local energy use and reducing transaction costs. Their simulation on the Ethereum platform confirms that blockchain can effectively optimize energy transactions and enhance the operational efficiency of VPPs, making it a viable solution for modern energy markets .

Similarly, [29] explore the use of blockchain technology in P2P energy trading to support new business models for prosumers. Their research highlights how blockchain enables direct communication between end-consumers and Distribution System Operators (DSOs) without the need for traditional intermediaries. Smart contracts are employed as virtual aggregators, facilitating transparent, distributed, and secure energy transactions. The paper also explores user-guided and automated auction mechanisms for energy trading, where prosumers can sell excess energy at competitive prices, benefiting both sellers and buyers. This decentralized approach to energy trading aligns with the broader goals of sustainability and empowers prosumers by providing them greater control over energy transactions. Blockchain's ability to optimize DERs within VPPs has also been explored extensively. In [30] present a novel framework that integrates blockchain with cloud services, grid operators, and forecasting systems to enhance the real-time bidding and scheduling of energy resources. Their multi-layered architecture leverages blockchain's decentralized nature to optimize DER administration, thereby improving grid stability and energy efficiency. The framework incorporates smart meters to facilitate data exchange between participants and DERs, ensuring that energy transactions are transparent and efficient. This study is particularly significant for its comprehensive approach to addressing the challenges of DER management in VPPs, highlighting how blockchain can support the real-time optimization of energy markets .

Chapter 3: Optimistic Ethereum Blockchain

3.1 Overview

Optimism (OP) is a Layer 2 (L2) scaling solution specifically created to tackle the scalability issues faced by Ethereum. Optimism is responsible for the development and operation of OP mainnet, which is an optimistic-rollup L2 solution and is constructed via optimistic roll-up technology. The present iteration is recognised as Optimism Bedrock. In the realm of blockchain architecture, a roll-up refers to a blockchain that obtains its security from a higher-level chain. Ethereum serves as the parent chain for Optimism. Optimism utilizes Ethereum to store and archive block data in a compressed format, resulting in cost savings and leveraging the robust security measures provided by the platform. This solution enhances the processing capacity of Ethereum by regularly grouping compressed transactions and distributing the associated costs among multiple users. The optimistic aspect of the technology operates under the assumption that submitted transactions (TXs) are inherently legitimate and accurate [31]. An invalid transaction has its on-chain obligations invalidated only when a fault proof is witnessed after a block is released. By utilising the security of the main blockchain and the efficiency benefits of compressing transactions, the cost structure and scalability of an optimistic roll-up are significantly enhanced. Optimism aims to achieve maximum compatibility with Ethereum and enhance its usefulness [32].

3.2 The Optimistic System

Optimism, categorised as a layer two solution, functions directly on the Ethereum Blockchain by employing smart contracts to replicate an altered version of the Ethereum Virtual Machine (EVM). This adapted version, called the OVM, is discussed further in section 3.3. The transition of users from the Ethereum mainnet to the Optimism network entails multiple processes [31], [32], [33].

1. Users choose the quantity of Ether they wish to transfer to the Optimism network.
2. They utilise the Optimism Gateway (https://gateway.optimism.io/) to commence the transfer.
3. The chosen Ether is subtracted from the user's wallet and secured under a layer 1 smart contract, which temporarily retains the cash and enables withdrawals when users revert to layer 1.
4. A secondary smart contract replicates the EVM, generating a corresponding quantity of Optimistic Ethereum tokens (for instance, depositing 100 Ether will yield 100 Optimistic Ethereum tokens for utilisation on the layer 2 network).
5. These tokens are subsequently utilised for transactions, including peer-to-peer transfers or contract interactions, all of which are aggregated into a rollup with further transactions.
6. The rollup is executed, hashed, and the outcome is transmitted back to layer 1. This hash is subject to a seven-day dispute period, enabling nodes to validate its accuracy. If the outcome

remains unchallenged, it is deemed genuine; if disputed and subsequently disproven, the accountable node is penalised.

7. To revert to layer 1, users' Optimistic Ethereum is extinguished, and a corresponding quantity of Ethereum is disbursed from the layer 1 contract. Withdrawals adhere to the identical seven-day verification time stipulated by Optimism's security framework.

3.3 Optimistic Virtual Machine (OVM)

State transitions represent the changes within the EVM that occur with every transaction. To prevent off-chain invalid state transitions, which could cause incorrect transactions when returning to Layer 1, Optimism introduced the OVM. This ensures that Layer 2 inherits the security protocols of the EVM and maintains the integrity of Layer 1. However, this process is complex, as inconsistencies such as block timestamps in Layer 2 can lead to errors in outputs [32], [33], [34].

3.4 Blocks

Blocks are generated at a rate of one every 2 seconds in Optimism Bedrock. Bedrock depends on a solitary entity, known as the Sequencer, for the manufacturing of blocks. The Sequencer is presently in the ownership and operation of the Optimism Foundation [34]. It holds a semi-trusted position within the Optimism technological stack.

The Sequencer is an Optimism node that performs three main functions:

1. It orders TXs and builds Layer 2 (L2) blocks.
2. It confirms transactions and changes the state.
3. It sends user TXs and state commitments to the Ethereum network.

The Sequencer fulfils two primary functions: (1)serving as a batcher and (2) acting as a proposer. The role of a batcher involves arranging and compacting a collection of recent transactions, and subsequently transmitting this data to the Ethereum network. Proposing involves making declarations regarding the L2 state after executing the batched transactions on the latest state. If the Sequencer is corrupted, it has the ability to censor transactions that the batcher chooses to ignore. Figure 3 illustrates the transaction flow on Optimism [35].

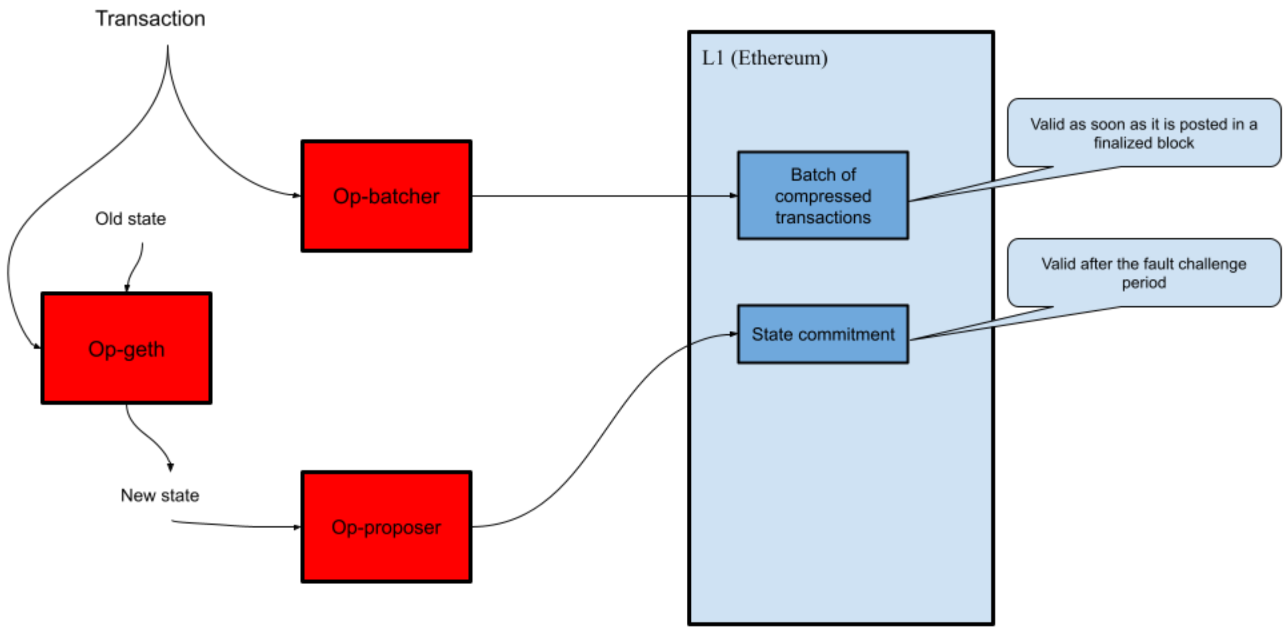


Figure 3: Graphic depiction of the flow of an Optimism transaction.

3.5 Scalability & Gas Costs

Scalability is one of the most critical challenges faced by blockchain networks, particularly Ethereum, which has been a leading platform for DApps and smart contracts. The mainnet of Ethereum processes transactions through a consensus mechanism that, while secure and decentralized, inherently limits its throughput to approximately 15-30 transactions per second (TPS). This limited capacity often leads to network congestion, resulting in high transaction fees (gas costs) and slower transaction finality, especially during periods of high demand such as popular NFT drops or surges in DeFi activity [25], [36].

Optimistic Ethereum addresses these scalability issues using a technology called optimistic rollups. Rollups allow transactions to be processed off-chain, with only the summarized data posted on-chain. This method reduces the amount of computation and storage required on the main Ethereum blockchain, significantly increasing transaction throughput and reducing costs [32], [33], [37]. The optimistic rollup approach assumes transactions are valid by default, hence the term "optimistic," and includes a mechanism for fraud proofs to be submitted if invalid transactions are detected. This approach drastically reduces the gas fees compared to Ethereum’s mainnet by minimizing the need for on-chain operations.

On Ethereum’s mainnet, transaction costs are determined by gas fees, which are paid in Ether (ETH). The gas price fluctuates based on network demand and is measured in gwei (a unit of ETH). For instance, during times of high congestion, gas fees can spike, resulting in costs of $10 to $50 or more per transaction. For complex transactions, such as those involving smart contracts in DeFi protocols, these fees can soar even higher, making Ethereum prohibitively expensive for many users [37], [38], [39], [40].

In contrast, Optimistic Ethereum offers a more scalable and cost-effective solution. By executing transactions off-chain and posting only the essential data on-chain, Optimistic Ethereum significantly lowers the gas fees. For example, a standard token transfer on Ethereum might cost around $20 during peak times, while the same transaction on Optimistic Ethereum could cost less than $1, demonstrating a cost reduction of over 90% [41]. Moreover, the enhanced scalability of Optimistic Ethereum allows it to process thousands of TPS, compared to Ethereum's limited 15-30 TPS, thereby alleviating congestion and further stabilizing gas prices.

These scalability improvements make Optimistic Ethereum a highly attractive option for developers and users seeking a more efficient and cost-effective blockchain environment, particularly for applications that require high transaction volumes and quick finality. The integration of Optimistic Ethereum into the broader Ethereum ecosystem reflects ongoing efforts to address the fundamental scalability issues of blockchain networks while maintaining the security and decentralization that are the hallmarks of Ethereum.

Table 3: Differences between Ethereum L1 and Optimistic Ethereum L2.

Feature	Ethereum Mainnet	Optimistic Ethereum
Transaction Costs	High transaction fees due to congestion; average gas fees can range from $10 to over $50 per transaction during peak times.	Significantly lower transaction fees; typically 10-100x cheaper than Ethereum mainnet, with fees often below $1 per transaction.
Scalability	Limited scalability with a throughput of approximately 15-30 TPS.	Enhanced scalability, capable of handling thousands of TPS due to off-chain execution and data aggregation on-chain.
Consensus Mechanism	Proof of Stake (PoS) as part of Ethereum 2.0 upgrade; previously Proof of Work (PoW).	Inherits security from Ethereum mainnet; uses optimistic rollups with fraud proofs for transaction validation.
Transaction Finality	Relatively slower transaction finality; dependent on network congestion and gas prices.	Faster transaction finality due to off-chain processing; however, it includes a challenge period for fraud proofs, which can impact finality time but is being optimized.
Gas Price Volatility	Highly volatile due to network demand; can spike during periods of high activity (e.g., during popular NFT launches or DeFi activity).	More predictable and stable gas fees; less influenced by mainnet congestion, benefiting from Layer-2 scalability improvements.
Security Model	Directly secured by Ethereum's blockchain; high level of security through decentralized PoS.	Secured by Ethereum's Layer-1; relies on fraud proofs to ensure correct off-chain execution, with the mainnet providing ultimate dispute resolution.

Network Congestion	Prone to congestion, leading to slower transaction times and higher fees during peak usage.	Significantly reduced congestion on Layer-2, as transactions are batched and posted on-chain, easing the load on the Ethereum mainnet.

3.6 Security

Optimistic Ethereum ensures security through a combination of off-chain execution, cryptographic commitments, and a robust fraud-proof system. The underlying security model relies on assuming transactions are valid unless proven otherwise within a designated dispute period, leveraging both mathematical mechanisms and economic incentives to maintain integrity [33], [34], [35], [42], [43].

1. Off-Chain Execution and State Transition:

Transactions are executed off-chain, where each transaction T_i results in a state transition from state S_i to state S_{i+1} expressed as:

$$S_{i+1} = T(S_i, T_i)$$

Here, T represents the state transition function, which processes the inputs of a transaction to determine the next state. By executing these transitions off-chain, Optimistic Ethereum achieves high throughput and cost efficiency without burdening the mainnet with the full computational load.

2. Batching and Merkle Tree Commitments:

Executed transactions are grouped into batches B, which are then submitted to Ethereum's mainnet. Each batch B can be represented as a sum of transactions:

$$B = \sum_{i=1}^{B} T_i$$

To ensure data integrity and availability, a cryptographic Merkle root M(B) is computed for the batch. The Merkle root serves as a cryptographic commitment to all the transactions within the batch and is calculated as follows:

$$M(B) = H(H(\ldots H(L_1, L_2), \ldots), L_n)$$

where L_i are the leaf nodes (hashes of individual transactions) and H is a cryptographic hash function, typically SHA-256. This Merkle root is published on the Ethereum mainnet, allowing any network participant to verify the validity of the transactions in the batch without needing to process all transaction details directly on-chain.

3. Fraud-Proof Mechanism and Dispute Resolution:

The core security mechanism of Optimistic Ethereum is its fraud-proof system, which allows validators to challenge any transaction within a batch during the dispute period. If a validator suspects a transaction T_i is invalid, they can submit a fraud proof, prompting on-chain execution of the transaction:

$$T(S_j, T_j) \neq S_{j+1}$$

If the executed result on-chain does not match the proposed off-chain state transition, the transaction is deemed fraudulent. Validators who correctly identify fraud are rewarded, while those responsible for fraudulent transactions face penalties, including the loss of staked assets:

$$P = S_{Stake} \cdot P$$

Where S_{Stake} is the amount staked by the verifier, and P is a penalty multiplier set by the protocol. This economic disincentive aligns the interests of validators with the security of the network, ensuring diligent monitoring of transaction validity.

4. Finality and State Updates:

Once the dispute period concludes without any successful challenges, the transaction batch is finalized, and the state changes are committed to the Ethereum mainnet. The mainnet updates its global state S_{Global} by applying the cumulative state changes ΔS derived from the finalized batch:

$$S_{Stake} = S_{Stake} + \Delta S$$

These updates include modifications to account balances, token transfers, and other relevant state transitions reflecting the outcome of the executed transactions.

5. Data Availability and State Integrity:

Optimistic rollups publish minimal data on the Ethereum mainnet, relying on the Merkle root to guarantee data availability and integrity. In the event of a dispute, the full transaction data and corresponding proofs are submitted, ensuring that any invalid state transitions are corrected through Ethereum's robust Proof of Stake (PoS) consensus mechanism. This layered approach balances scalability with security, making Optimistic Ethereum an effective solution for enhancing the Ethereum ecosystem.

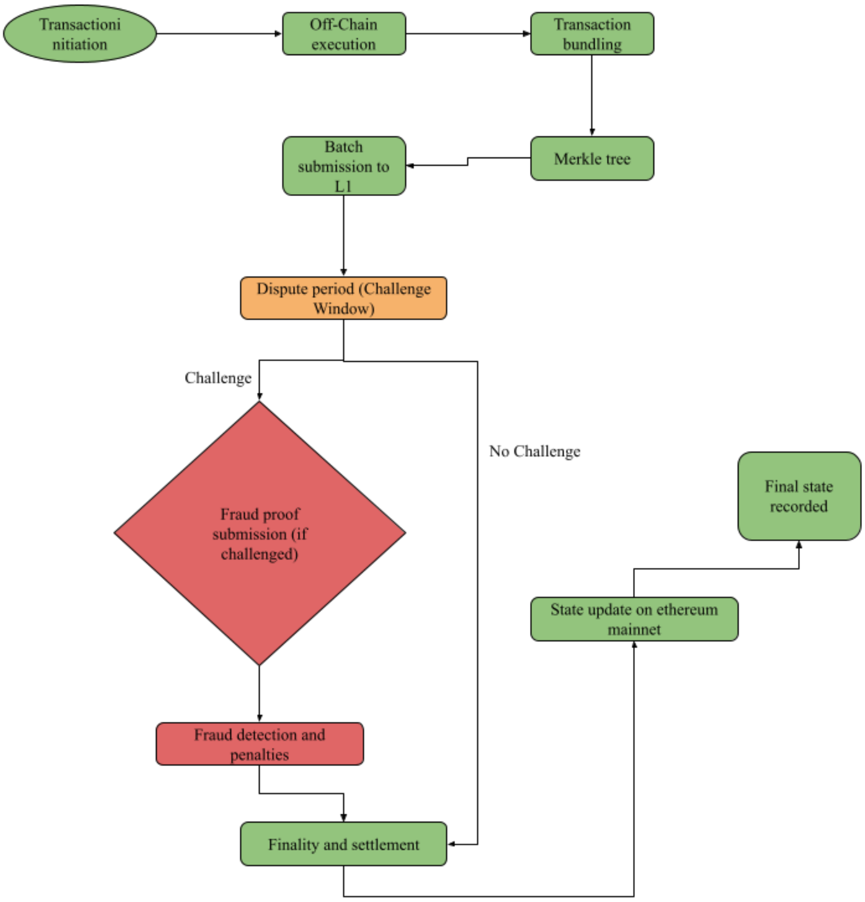


Figure 4: Froud proof and state integrity on Optimistic Ethereum blockchain.

Chapter 4: Conceptual Approach

4.1 Research Design

This thesis implementation does not integrate financial data or operational data from systems like SCADA or data from smart meters, but instead focuses on building a demo system that illustrates the potential functionalities and benefits of such an approach. The research design details the technologies used, the rationale behind their selection, and the expected outcomes from testing the system within the Optimistic Ethereum environment.

Research Scope and Objectives: The core objective of this research is to develop a conceptual prototype that automates the creation, management, and trading of VPPAs using blockchain technology. This system aims to showcase the benefits of decentralization, transparency, and automation in energy trading without delving into complex integrations with financial or operational data. By developing a demonstrative model, the project provides insights into how blockchain can be used to streamline renewable energy agreements and explores the scalability and security aspects within a Layer-2 environment.

Technology and Design Choices: The smart contracts for this project were developed using Solidity version 0.5.16, which was the prevalent version at the time of initial development. Solidity 0.5.16 was chosen because it was widely adopted and stable, offering essential security features such as improved function visibility, stricter type checks, and better error handling. These features were critical in ensuring the robustness of the contracts, particularly given the financial nature of VPPAs. Additionally, using Solidity >0.5.x (general versions of > 0.5.x) allowed compatibility with various Ethereum development tools, facilitating a smoother development and testing process [44].
The project utilizes Optimistic Ethereum as the Layer-2 solution for its scalability benefits. Optimistic Ethereum enhances transaction throughput and reduces costs by processing transactions off-chain and settling them on the Ethereum mainnet after a dispute period. This choice was made to demonstrate how Layer-2 solutions can effectively scale energy trading platforms, making them more accessible and efficient. The smart contracts are modular, designed to handle producer and buyer registrations, VPPA creation and management, and energy trading functions, all while ensuring a secure and transparent environment [45].

Conceptual Demonstration and Expected Outcomes: This prototype is intended to show how blockchain-based systems can simplify the VPPA process by automating contract execution, providing decentralized verification, and offering transparent energy accounting. By deploying the smart contracts on the Optimistic Ethereum testnet, the project aims to validate the technical feasibility of this approach without needing to simulate real-world financial transactions or integrate external data sources. This conceptual model serves as a foundational demonstration of how blockchain can optimize the VPPA process, highlighting potential pathways for future enhancements.

Expected outcomes include demonstrating the system’s ability to handle key functionalities like contract automation, dispute resolution, and transparent transaction logging in a scalable manner. The project aims to illustrate how using a Layer-2 solution like Optimistic Ethereum can lower costs and improve transaction speeds, providing a clear pathway for how such a system could be scaled in real-world applications.

Testing and Evaluation: Testing will be conducted on the Optimistic Ethereum testnet (OP Sepolia) to evaluate the system’s performance under various scenarios. The focus will be on assessing transaction efficiency, scalability, and security within the Layer-2 environment. Specific metrics of interest include gas costs, transaction latency, and the robustness of the fraud-proof system. By testing in Optimistic Ethereum, the project aims to capture the practical benefits of off-chain processing and the impact of Layer-2 scaling solutions on decentralized energy trading systems.
The testing phase will help validate the conceptual design and provide valuable insights into the operational characteristics of blockchain-based VPPA management [46]. This approach will highlight the advantages and challenges of using Optimistic Ethereum, offering a basis for future research and potential real-world deployment of similar systems in the energy sector.

4.2 Programming languages

Programming languages that compile to Ethereum Virtual Machine (EVM) code include Solidity, Serpent, LLL (Low-Level Lisp-like Language), and Vyper. Among these, Solidity is the most widely used language within the Ethereum ecosystem due to its developer-friendly syntax, which is somewhat reminiscent of JavaScript but more accurately reflects the structure and object-oriented nature of languages like C++ or Java. Solidity's object-oriented approach allows developers to create complex and reusable code structures, making it particularly suitable for the design of sophisticated smart contracts.

Solidity is designed to compile code into EVM bytecode, which is executed by the Ethereum blockchain. The Solidity compiler, known as "solc", is responsible for transforming Solidity code into EVM bytecode and generating the Application Binary Interface (ABI), which is a JSON representation of the smart contract’s functions, events, and data structures. The ABI and EVM bytecode are essential components for deploying and interacting with smart contracts on the blockchain [44], [47].

For this project, Solidity is the language of choice due to its extensive support within the Ethereum community and its compatibility with the Optimistic Ethereum network. Importantly, Optimistic Ethereum is fully EVM-compatible, meaning that smart contracts written in Solidity and other EVM-compatible languages can be deployed on Optimistic Ethereum with minimal modifications [48].

The EVM is the runtime environment that executes smart contracts on the Ethereum blockchain, and it serves as the computational engine for both Ethereum and its Layer-2 solutions, including Optimistic Ethereum. Optimistic Ethereum maintains EVM compatibility, meaning that it supports the same bytecode and execution logic as the Ethereum mainnet. This compatibility ensures that smart contracts developed for Ethereum can be seamlessly migrated to Optimistic Ethereum, leveraging its enhanced scalability without the need for rewriting or extensive modifications [49].

By maintaining EVM compatibility, Optimistic Ethereum allows developers to use the same development tools, libraries, and languages (like Solidity) that they are familiar with on Ethereum. This also ensures that smart contracts running on Optimistic Ethereum benefit from the security and decentralized trust model of the Ethereum mainnet, as all transactions ultimately settle on the Layer-1 blockchain after passing through a dispute resolution mechanism [50]. This relationship makes Optimistic Ethereum an attractive platform for deploying scalable smart contracts, as it combines the high performance of Layer-2 processing with the robust security of the EVM on the Ethereum mainnet.

4.3 Creating Smart Contracts

In the development of our system, the creation of smart contracts was essential to automate and optimize the management of VPPAs on the Optimistic Ethereum blockchain. The smart contracts were designed to handle key aspects of the VPPA lifecycle, including registration of participants, creation and management of agreements, and energy trading, while ensuring transparency and security throughout the process.

Assumptions and Design Considerations: In designing the smart contracts, we operated under several assumptions tailored to the needs of our demonstration. One critical assumption was the need for transparency in representing energy transactions and ownership, which led us to utilize blockchain for storing and verifying these records. Our goal was to simulate how VPPAs could be managed in a decentralized and efficient manner, without integrating real-world financial data, smart meters or SCADA systems. Instead, we focused on developing a conceptual framework that illustrates the potential benefits of blockchain technology in energy agreements.

Smart Contract Structure: To cover the various functionalities required for VPPAs, we developed three (3) main smart contracts, each serving a distinct purpose:

1. Producer and Buyer Registries: The first set of contracts manages the registration and deregistration of energy producers and buyers. These registries ensure that only authorized participants can interact with VPPA functions, thus maintaining the integrity and security of the system.
2. PPA Management Contract: The core contract facilitates the creation, approval, and trading of PPAs. This contract allows producers to create PPAs with predefined terms, such as price, duration, and the amount of energy to be traded. Buyers can then claim these PPAs based on their specific needs or bid for auction-based PPAs.
3. Energy Trading Contract: This contract manages the trading of energy units between producers and buyers. It includes functionalities to notify the network of available energy, execute trades based on PPA terms, and log all transactions for future reference.

Focus on Demonstrating Potential Outcomes: Since the primary aim was to demonstrate how such a system could function in a real-world scenario, we emphasized the practical aspects of VPPA management rather than focusing on granular energy consumption data. For example, the energy trading contract allows for the exchange of energy based on available kWhs linked to specific PPAs, showcasing how the system can facilitate dynamic energy transactions and settlement on the blockchain.

Implementation on Optimistic Ethereum: The smart contracts were developed using Solidity and deployed on the Optimistic Ethereum network to leverage its Layer-2 scaling benefits, including reduced transaction costs and increased throughput. Optimistic Ethereum’s EVM compatibility ensured that our contracts could seamlessly integrate with existing Ethereum tools and libraries, facilitating a smooth development and testing process.

Chapter 5: Implementation

5.1 Technical Requirements

The implementation of this project required a well-structured development environment, with the use of industry-standard tools and frameworks to ensure that the smart contracts for VPPAs are secure, scalable, and efficiently deployed. The following technical requirements outline the key components used in the development and testing process:

Blockchain Platform: Optimistic Ethereum

- Optimistic Ethereum was selected as the Layer-2 scaling solution to address the limitations of transaction throughput and gas fees on Ethereum's Layer-1. By processing transactions off-chain and posting them back to Ethereum after a dispute period, Optimistic Ethereum allows for faster, cheaper execution of smart contracts.
- Testnet: The project used the OP Sepolia testnet for Optimistic Ethereum as the testing ground for contract deployment. OP Sepolia provides a controlled environment where smart contracts can be tested under real-world conditions before moving to the mainnet.

Smart Contracts

- Solidity Compiler (0.5.16): The project uses Solidity version >= 0.5.0 <0.8.0 to develop the smart contracts.
- Cryptographic Hash function: SHA-512, ECDSA.
- Truffle Framework (v5.1.54): The Truffle framework was employed for developing, compiling, and deploying smart contracts. It provides integration with the OP Sepolia testnet via Ganache, and supports contract management, testing, and migrations. Truffle's versatility and compatibility with Optimistic Ethereum make it ideal for this project.
- Ganache: Used as a local blockchain emulator to run tests and simulate blockchain operations, Ganache allows developers to test how contracts will behave under different conditions before deploying them to the testnet.
- Remix IDE: Remix was used as an additional tool for quickly writing, testing, and debugging Solidity code in a browser-based environment. It supports Solidity syntax and integrates well with Metamask for deployment.

Wallet and Deployment Tools

Metamask: Metamask was used as the main wallet for deploying and interacting with smart contracts on the OP Sepolia testnet. Its seamless integration with both Remix and Truffle makes it an essential tool for managing accounts, signing transactions, and monitoring deployments.

Mathematical Libraries

OpenZeppelin: Due to Solidity's native limitations in performing arithmetic operations securely, OpenZeppelin’s libraries were incorporated. The OpenZeppelin SafeMath library was used to prevent common errors like overflows and underflows during mathematical operations, ensuring the integrity of contract logic.

Front-End Development

React JS (v17.0.1): React JS was chosen for building the front-end interface for interacting with the deployed smart contracts. This framework provides a dynamic and modular approach to developing user interfaces, enabling seamless integration with Web3 libraries for blockchain interaction. It allows users to interact with contracts deployed on the Optimistic Ethereum network in a user-friendly manner.

5.2 Smart Contract Development

The development of our smart contracts focuses on managing energy transactions and tracking renewable energy certificates using a decentralized, blockchain-based system. These smart contracts, written in Solidity, facilitate the creation, trading, and verification of VPPAs. They ensure transparency, traceability, and trust between energy producers (sellers) and buyers, while adhering to the principles of decentralization and security. They smart contracts were deployed on the Rinkeby test net and evaluated.

5.2.1 Constraints and Conditions

In our smart contract system for energy trading and PPA creation, various constraints and conditions govern how contracts are created, validated, and executed. These constraints are crucial for ensuring the system's integrity, fairness, and compliance with energy transaction rules. Below, we describe these rules mathematically, highlighting the logic behind energy trading and PPA creation.

1. Contract Creation Constraints:

For a contract cc, certain conditions must be met to ensure it is valid and executable. These conditions focus on the seller's available energy and the price per kilowatt-hour (kWh).
Energy Availability Constraint: The seller’s available energy scsc must be less than or equal to the amount of energy e_c offered in the PPA.

$$s_c \leq e_c$$

2. Price Constraint:

The agreed price p_c in the contract must be greater than or equal to a minimum price Min_Price set by the system. This ensures that all contracts respect a base market price and avoid exploitation.

$$p_c \leq Min\_Price$$

Together, these constraints ensure that sellers do not promise more energy than they can provide and that contracts maintain market price integrity.

3. Energy Transaction Validation:

For an energy transaction t to be valid, it must satisfy specific conditions involving both parties' registration statuses and the availability of energy for the transaction.

The transaction t is valid if the allocation function $A(p, c)$ which denotes the amount of energy from the producer p in contract c is greater than or equal to the energy requested in the transaction E_t. Additionally, both the producer and the buyer must be registered in the system.

$$Valid(t) = 1 \; if \; A(p, c) \geq \; E_t \; and \; Reg_p = 1 \; and \; Reg_b = 1$$

Where:

- Reg_p and Reg_b are the registration status of the producer and buyer, respectively, and both must be equal to 1 (i.e., both parties must be registered).

5.2.2 Contract Structure

The system is modular, designed to handle distinct responsibilities through separate contracts. This modular approach enhances the maintainability and scalability of the overall system. At its core, the system includes two main components:

ProducerRegistry: This contract is responsible for managing the registration of energy producers. Only registered producers can create and offer energy contracts, ensuring that only verified entities can participate in the marketplace. Producers can register and deregister themselves, emitting relevant events for transparency (`producerRegistered` and `producerDeregistered`).

PPABuyerRegistry: This contract automatically registers buyers who purchase PPAs, assigning them a unique identifier (buyer ID). The contract ensures that only verified buyers can claim or purchase PPAs, enabling secure and controlled transactions.

Algorithm for registering and deregistering a buyer or producer:

```
Step 1: Algorithm RegistryManagement
Step 2:    If producer or buyer wants to register then:
Step 3:        If entity is a producer:
Step 4:            Call registerProducer()
Step 5:            Add producer to producers mapping
Step 6:            Emit producerRegistered event
Step 7:        End_if
Step 8:        If entity is a buyer:
Step 9:            Call registerPPABuyer(buyer)
Step 10:           Increment buyer ID
Step 11:           Add buyer to ppaBuyers mapping with ID
Step 12:           Emit buyerRegistered event
Step 13:       End_if
Step 14:   End_if
Step 15:   If producer or buyer wants to deregister then:
Step 16:       If entity is a producer:
Step 17:           Call deregisterProducer()
Step 18:           Remove producer from producers mapping
Step 19:           Emit producerDeregistered event
Step 20:       End_if
Step 21:       If entity is a buyer:
```

```
Step 22:           Call deregisterPPABuyer(buyer)
Step 23:           Set buyer ID to 0 in ppaBuyers mapping
Step 24:           Emit buyerDeregistered event
Step 25:       End_if
Step 26:   End_if
Step 27: End_RegistryManagement
```

5.2.3 Contract Creation Functions

The smart contracts include two primary functions for creating energy agreements: `corporatePPA` and `createPPA`. These two functions provide different methods of entering energy agreements, depending on the nature of the relationship between producers and buyers:

corporatePPA: This function is used for agreements that have predefined terms between a producer and a buyer, particularly suited for large companies. Both parties benefit from long-term price guarantees, which protect them from the volatility of energy markets. This setup is ideal for established companies that have already agreed on energy pricing and contract terms, seeking stability in their energy procurement.

createPPA: This function allows producers to create ad-hoc energy contracts without pre-agreed terms. The energy producer can offer energy on the marketplace, allowing smaller buyers to bid on energy contracts. The buyer automatically selects the lowest-priced PPA using the `claimAuctionPPA` function. This type of PPA is typically used by smaller entities or energy producers who seek to secure buyers early in the project development phase, thus facilitating investment in new green energy projects.

Algorithm for creating PPAs:

```
Step 1: Algorithm CreatePPA
Step 2: If producer wants to create a PPA then:
Step 3: Call createPPA(kwhPrice, startDay, endDay)
Step 4: Generate unique contract ID using Counters
Step 5: Validate startDay >= current timestamp
Step 6: Validate endDay > startDay
Step 7: Validate kwhPrice >= 1 cent
Step 8: Add new PPA to listOfPPAs
Step 9: Emit createdPPA event
Step 10: End_if
Step 11: End_CreatePPA
Step 12: Algorithm CreateCorporatePPA
Step 13: If producer wants to create a corporate PPA then:
Step 14: Call corporatePPA(buyer, agreedKwhPrice, startDay, endDay, id)
Step 15: Validate agreed terms: startDay, endDay, agreedKwhPrice
Step 16: Add new corporate PPA to corporatePPAList
Step 17: Issue PPA via Registry contract
Step 18: Emit createdCorpPPA event
Step 19: End_if
Step 20: End_CreateCorporatePPA
Step 21: Algorithm ClaimPPA
Step 22: If buyer wants to claim a PPA then:
```

```
Step 23: Call claimPPA(id)
Step 24: Search for PPA in listOfPPAs
Step 25: If PPA matches conditions then:
Step 26: Move PPA to approvedPPAs list (Appas)
Step 27: Emit purchasedPPA event
Step 28: End_if
Step 29: End_if
Step 30: End_ClaimPPA
Step 31: Algorithm AcceptCorporatePPA
Step 32: If buyer wants to accept a corporate PPA then:
Step 33: Call acceptCorporatePPA(id)
Step 34: Search for corporate PPA in corporatePPAList
Step 35: If PPA matches conditions then:
Step 36: Move PPA to approvedPPAs list (Appas)
Step 37: Emit acceptedCorpPPA event
Step 38: End_if
Step 39: End_if
Step 40: End_AcceptCorporatePPA
```

5.2.4 ERC 1888 and 1155

In the realm of Ethereum token standards, ERC-1155 and ERC-1888 both introduce innovative functionalities for handling multiple assets and supporting complex token ecosystems. These token standards play a crucial role in streamlining blockchain applications, particularly in decentralized energy markets, as they allow for more efficient, scalable, and flexible operations.

ERC-1155: Multi-Token Standard

The ERC-1155 standard was introduced to address the limitations of earlier token standards like ERC-20 and ERC-721. While ERC-20 focuses on fungible tokens (like cryptocurrencies) and ERC-721 on NFTs, ERC-1155 combines the best of both worlds. It allows for the management of multiple token types (both fungible and non-fungible) within a single contract. This standard significantly improves efficiency and scalability in token transfers by reducing the gas costs associated with batch operations.

For the purposes of a decentralized energy marketplace, ERC-1155 provides the ability to manage various energy-related assets such as energy credits (fungible) and unique green energy certifications (non-fungible) in one unified contract. For example, it could be used to represent both energy tokens and certification tokens under the same umbrella, reducing complexity and costs in energy trading.

Key Features of ERC-1155:

- **Batch transfers**: ERC-1155 allows multiple assets to be transferred in a single transaction, which reduces gas fees and network congestion.
- **Support for both fungible and non-fungible tokens**: This flexibility enables the integration of different token types, such as energy credits and unique certifications.
- **Efficient storage**: Instead of storing token information in multiple contracts, ERC-1155 stores all relevant token data in a single contract, improving gas efficiency.

In energy markets, these features streamline the trading of energy assets and certifications, making it easier to integrate various forms of renewable energy certificates or carbon credits into blockchain platforms.

ERC-1888: EACs

ERC-1888 was designed specifically for energy attribute certificates, making it highly relevant for energy trading applications. EACs, such as GOs in Europe or RECs in the U.S., verify the origin of energy generated from renewable sources. ERC-1888 provides a standard for these certificates, ensuring they can be securely and transparently managed on the Ethereum blockchain.

ERC-1888 ensures that these certificates can be tokenized, traded, and validated in decentralized energy markets. The token standard is optimized for the energy sector, particularly for platforms seeking to automate the issuance and trading of green energy certificates, such as those used in VPPAs.

Key Features of ERC-1888:

- **Issuance and tracking of certificates**: ERC-1888 is built to represent energy generation from renewable sources and track ownership over time, ensuring certificates are not double-counted.
- **Cross-border and cross-standard compatibility**: The token standard is compatible with multiple regulatory systems, making it ideal for international energy markets.
- **Immutable and transparent validation**: As with other Ethereum-based tokens, the blockchain's immutability ensures that once a certificate is issued, it cannot be altered, providing trust to the system.

In an academic context, ERC-1888 can be viewed as a specialized token standard created to facilitate more efficient and verifiable energy attribute trading on a global scale. For our thesis, this standard exemplifies how blockchain can decentralize and automate critical energy transactions while maintaining high levels of transparency and trust.

We chose to use both ERC-1888 and ERC-1155 in this thesis to support the flexibility and efficiency needed for the green energy trading platform we developed [23], [24].

ERC-1155 is a highly flexible Ethereum token standard that allows for the management of multiple token types (fungible, semi-fungible, and non-fungible) under a single contract. This is useful for the dynamic needs of our platform, where both energy certificates and various assets might be traded. By utilizing ERC-1155, we can efficiently manage different types of tokens (such as energy tokens or certificates) in bulk operations. This reduces the gas costs associated with managing large-scale transactions, which is vital for a platform handling numerous trades and certificate claims.

ERC-1888, built on top of ERC-1155, is specifically designed for EACs and their claim mechanisms, ensuring transparency and verification of the green energy traded through our platform. This standard allows certificates to be issued and claimed securely, making it particularly suited to renewable energy markets where credibility and tracking the origin of energy is essential. By implementing ERC-1888, we support a verifiable and decentralized system for tracking and claiming green energy certificates, an essential feature for building trust and facilitating transactions between producers and consumers in an eco-friendly energy marketplace.

5.2.5 iRegistry and EACs

A key innovation in the system is the integration of **iRegistry**, which plays a vital role in tracking renewable energy certificates such as EACs. These certificates are essential for ensuring that the energy traded and consumed is from renewable sources. The `iRegistryinterface` allows the system to manage these certificates efficiently by:

Issuing Certificates: When a PPA is created and energy is produced, the system interacts with `iRegistry` to issue EACs, confirming the production and consumption of green energy. These certificates are critical for verifying that the energy generated comes from renewable sources.

```
interface ERC1888 is IERC1155 {

    struct Certificate {
        uint256 topic;
        address issuer;
        bytes validityData;
        bytes data;
    }

   event IssuanceSingle(address indexed _issuer, uint256 indexed _topic, uint256 _id, uint256 _value);
   event IssuanceBatch(address indexed _issuer, uint256 indexed _topic, uint256[] _ids, uint256[] _values);

   event ClaimSingle(address indexed _claimIssuer, address indexed _claimSubject, uint256 indexed _topic, uint256 _id, uint256 _value, bytes _claimData);
   event ClaimBatch(address indexed _claimIssuer, address indexed _claimSubject, uint256[] indexed _topics, uint256[] _ids, uint256[] _values, bytes[] _claimData);

   function issue(address _to, bytes calldata _validityData, uint256 _topic, uint256 _value, bytes calldata _issuanceData) external returns (uint256);
   function batchIssue(address _to, bytes memory _issuanceData, uint256 _topic, uint256[] memory _values, bytes[] memory _validityCalls) external returns(uint256[] memory);

   function safeTransferAndClaimFrom(address _from, address _to, uint256 _id, uint256 _value, bytes calldata _data, bytes calldata _claimData) external;
   function safeBatchTransferAndClaimFrom(address _from, address _to, uint256[] calldata _ids, uint256[] calldata _values, bytes calldata _data, bytes[] calldata _claimData) external;

   function getCertificate(uint256 _id) external view returns (address issuer, uint256 topic, bytes memory validityCall, bytes memory data);
   function claimedBalanceOf(address _owner, uint256 _id) external view returns (uint256);
   function claimedBalanceOfBatch(address[] calldata _owners, uint256[] calldata _ids) external view returns (uint256[] memory);
}
```

Figure 5: Interface for EACs.

Minting Certificates: After the issuance of the certificate, the system mints the certificates as ERC1888 tokens using ERC1155 (through the `Issuer.sol` file code and `Privateissuer.sol`), which represent the renewable energy attributes (e.g., 1 MWh of green energy). These tokens can be traded or transferred, providing a transparent and verifiable record of green energy consumption.

```
struct CertificationRequest {
    address owner; // Owner of the request
    bytes data;
    bool approved;
    bool revoked;
    address sender;  // User that triggered the request creation
}
```

Figure 6: Structure of Green Energy Certificates.

```
function requestCertificationFor(bytes memory _data, address _owner) public returns (uint256) {
    uint256 id = ++_latestCertificationRequestId;

    _certificationRequests[id] = CertificationRequest({
        owner: _owner,
        data: _data,
        approved: false,
        revoked: false,
        sender: _msgSender()
    });

    emit CertificationRequested(_owner, id);

    return id;
}
```

Figure 7: Function to request a Green Energy Certificate.

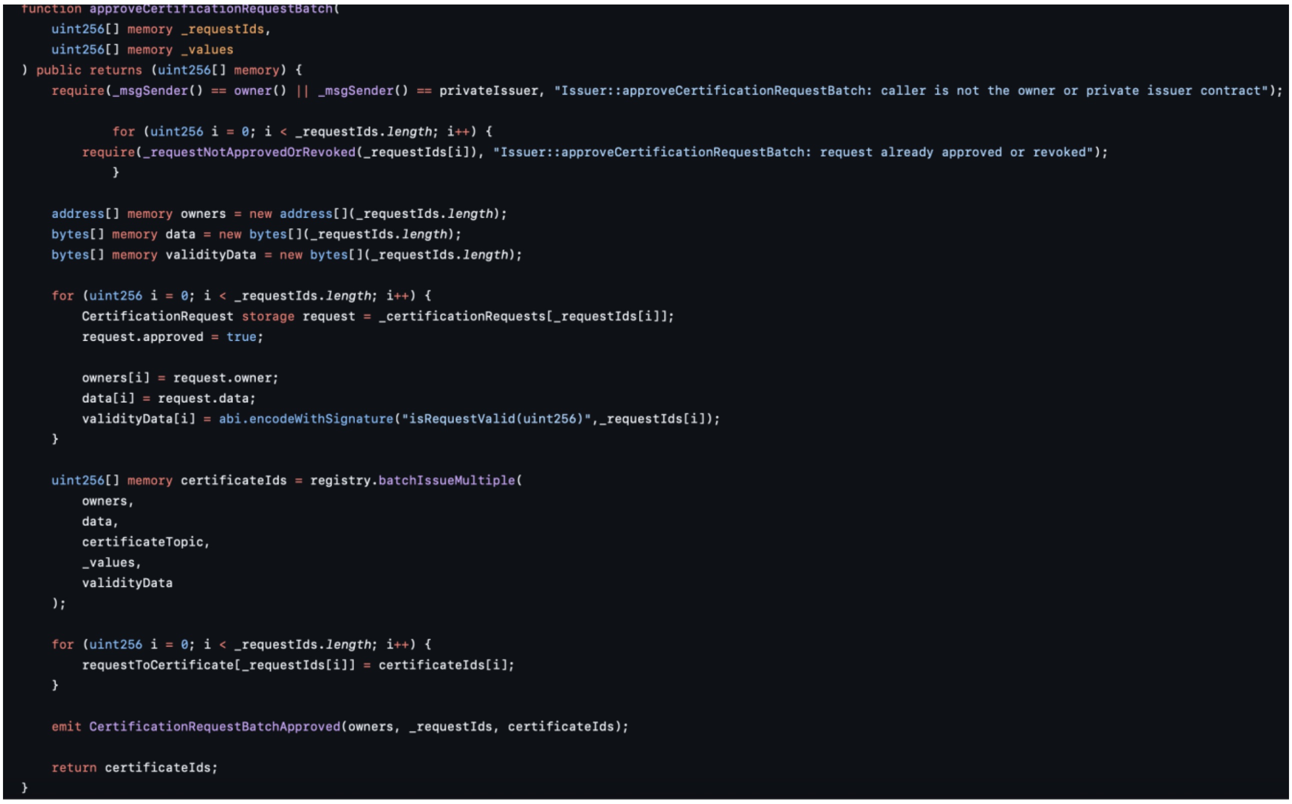
```
function requestCertificationForBatch(bytes[] memory _data, address[] memory _owners) public returns (uint256[] memory) {
    uint256[] memory requestIds = new uint256[](_data.length);

    for (uint256 i = 0; i < _data.length; i++) {
        uint256 id = i + _latestCertificationRequestId + 1;

        _certificationRequests[id] = CertificationRequest({
            owner: _owners[i],
            data: _data[i],
            approved: false,
            revoked: false,
            sender: _msgSender()
        });

        requestIds[i] = id;
    }

    emit CertificationRequestedBatch(_owners, requestIds);

    _latestCertificationRequestId = requestIds[requestIds.length - 1];

    return requestIds;
}
```

Figure 8: Function to request multiple Green Energy Certificates.

Verification and Validation: The `iRegistry` also handles certificate validation, ensuring that the green energy claims made by producers are accurate. The validate function ensures that any claims made by a producer regarding green energy generation are verifiable, preventing fraud and ensuring compliance with environmental regulations.

```
function approveCertificationRequest(
    uint256 _requestId,
    uint256 _value
) public returns (uint256) {
    require(_msgSender() == owner() || _msgSender() == privateIssuer, "Issuer::approveCertificationRequest: caller is not the owner or private issuer contract");
    require(_requestNotApprovedOrRevoked(_requestId), "Issuer::approveCertificationRequest: request already approved or revoked");

    CertificationRequest storage request = _certificationRequests[_requestId];
    request.approved = true;

    uint256 certificateId = registry.issue(
        request.owner,
        abi.encodeWithSignature("isRequestValid(uint256)",_requestId),
        certificateTopic,
        _value,
        request.data
    );

    requestToCertificate[_requestId] = certificateId;

    emit CertificationRequestApproved(request.owner, _requestId, certificateId);

    return certificateId;
}
```

Figure 9: This function, is responsible for approving green energy certification requests by authorized entities and issuing certificates through the blockchain registry.



```
function approveCertificationRequestBatch(
    uint256[] memory _requestIds,
    uint256[] memory _values
) public returns (uint256[] memory) {
    require(_msgSender() == owner() || _msgSender() == privateIssuer, "Issuer::approveCertificationRequestBatch: caller is not the owner or private issuer contract");

            for (uint256 i = 0; i < _requestIds.length; i++) {
        require(_requestNotApprovedOrRevoked(_requestIds[i]), "Issuer::approveCertificationRequestBatch: request already approved or revoked");
            }

    address[] memory owners = new address[](_requestIds.length);
    bytes[] memory data = new bytes[](_requestIds.length);
    bytes[] memory validityData = new bytes[](_requestIds.length);

    for (uint256 i = 0; i < _requestIds.length; i++) {
        CertificationRequest storage request = _certificationRequests[_requestIds[i]];
        request.approved = true;

        owners[i] = request.owner;
        data[i] = request.data;
        validityData[i] = abi.encodeWithSignature("isRequestValid(uint256)",_requestIds[i]);
    }

    uint256[] memory certificateIds = registry.batchIssueMultiple(
        owners,
        data,
        certificateTopic,
        _values,
        validityData
    );

    for (uint256 i = 0; i < _requestIds.length; i++) {
        requestToCertificate[_requestIds[i]] = certificateIds[i];
    }

    emit CertificationRequestBatchApproved(owners, _requestIds, certificateIds);

    return certificateIds;
}
```

Figure 10: This function approving multiple green energy certificates.

These two functions in figure 11 manage the issuing of certifications for green energy requests. The issue function allows the issuance of a single certification directly to a specified address without requiring a separate manual approval process. The address (_to), the value, and any additional data are provided, and the function returns a certification ID after validating the request.
The issueBatch function is designed for batch processing of multiple certificates at once. It takes multiple addresses, values, and request IDs, issuing a batch of certificates in a single transaction, streamlining the certification process by avoiding multiple manual steps.

```
/// @notice Directly issue a certificate without going through the request/approve procedure manually.
function issue(address _to, uint256 _value, bytes memory _data) public onlyOwner returns (uint256) {
    uint256 requestId = requestCertificationFor(_data, _to);

    return approveCertificationRequest(
        requestId,
        _value
    );
}

/// @notice Directly issue a batch of certificates without going through the request/approve procedure manually.
function issueBatch(address[] memory _to, uint256[] memory _values, bytes[] memory _data) public onlyOwner returns (uint256[] memory) {
    uint256[] memory requestIds = requestCertificationForBatch(_data, _to);

    return approveCertificationRequestBatch(
        requestIds,
        _values
    );
}
```

Figure 11: Functions for direct issuance of certificates.

5.2.6 Event-Driven Architecture and Transparency

The contracts utilize an event-driven architecture to enhance transparency and efficiency. Every key action within the contract, such as the registration of producers, the creation and acceptance of PPAs, and the trading of energy, emits events that can be tracked externally:

- **Producer Events**: The system emits `producerRegistered` and `producerDeregistered` events whenever a producer joins or leaves the marketplace.
- **PPA Events**: When a PPA is created, accepted, or completed, events like `createdPPA`, `acceptedCorpPPA`, and `purchasedPPA` are emitted. This allows all stakeholders to monitor the lifecycle of PPAs in real-time.

5.2.7 Energy Trading and Auctions

Energy trading in the system is facilitated by two key functions: buyPPAKwhs and energyTradingPPA. These functions allow buyers to purchase energy directly from producers based on available energy (kWh) and contract terms:

- **buyPPAKwhs**: This function allows buyers to purchase available energy from a specific PPA. Buyers provide the ID of the PPA, and the contract checks if energy is available for purchase. If energy is available, it is transferred to the buyer, and the PPA is updated to reflect the transaction.
- **energyTradingPPA**: In cases where buyers wish to purchase a specific amount of energy (kWh), this function enables buyers to select the amount they want to purchase from available energy sources. This is particularly useful for buyers with specific energy requirements.

Algorithm for managing available energy based on closed PPAs and energy supply:

```
Step 1: Algorithm ManageEnergyAvailabilityAndPurchase
Step 2:    If producer wants to declare available energy then:
Step 3:        Call availableKwhs(buyer, energy, idOfMatchPPA)
Step 4:        Validate energy amount is >= 1 kWh
Step 5:        Add available energy to listOfkwhs
Step 6:        Emit availableEnergyNotification event
Step 7:    End_if
Step 8:    If buyer wants to purchase energy then:
Step 9:        If buyer wants to purchase based on PPA:
Step 10:           Call buyPPAKwhs(idOfPPA)
Step 11:           Search for matching energy in approved PPAs
Step 12:           If matching energy found then:
Step 13:               Transfer energy to buyer
Step 14:               Update energy records
Step 15:               Call iRegistry.issue() to issue EAC for the buyer (to certify green energy)
Step 16:               Emit purchasedPPA event
Step 17:           End_if
Step 18:       End_if
Step 19:       If buyer wants to purchase a specific energy amount:
Step 20:           Call energyTradingPPA(idOfContract, buyEnergy)
Step 21:           Validate energy availability and contract terms
Step 22:           Transfer specified amount of energy to buyer
Step 23:           Call iRegistry.issue() to issue EAC for the buyer (to certify green energy)
Step 24:           Emit purchasedPPA event
Step 25:       End_if
Step 26:   End_if
Step 27: End_ManageEnergyAvailabilityAndPurchase
```

We successfully deployed our smart contracts on both the **Sepolia** and **Optimism Sepolia** testnets to fully test and evaluate the functionalities in diverse environments. After careful consideration, we chose Sepolia for its close alignment with Ethereum's mainnet environment, and Optimism Sepolia to leverage the benefits of Layer-2 scaling with Optimistic Rollups. Using **Remix IDE** in conjunction with **MetaMask**, we connected to each network for seamless deployment. During this process, we encountered and resolved issues with gas estimation and JSON-RPC errors by fine-tuning our contract code and adjusting gas limits. Once deployed, we verified the contracts on Etherscan, making them publicly accessible for further testing and validation. The live contracts address on Optimism Sepolia is: **0xb10CB74dad7f68C75Ffd656754A7C1568221cE48** and on Sepolia is: **0x1F2A9F127485552599a181428a138BaAeB843b55**

5.3 Integration with Existing Energy Market Systems

The project outlined in this thesis demonstrates a framework for integrating blockchain-based energy trading platforms, specifically VPPAs, with existing energy market systems. This integration leverages blockchain's transparency, decentralization, and automation capabilities to address key challenges faced by traditional energy markets, including inefficiencies, lack of traceability, and barriers to participation for smaller energy producers and buyers.

5.3.1 Integration Points with Traditional Energy Markets

Interoperability with Energy Grids and Market Operators: One of the core aspects of integrating blockchain technology with existing energy markets is ensuring compatibility with the established energy grid infrastructure and market operators. The energy produced and consumed under the VPPAs must be reported and tracked in alignment with traditional grid operations. Our system achieves this by leveraging EACs, such as GOs, which are recognized by traditional energy markets for certifying the source of renewable energy. The EACs issued through our smart contracts are verifiable and can be integrated with the records of national grid operators, enabling seamless coordination between the blockchain-based system and the existing grid.

Regulatory Compliance and Reporting: To ensure compatibility with the regulatory requirements of different jurisdictions, our system integrates the issuance and validation of EACs through the `iRegistry` smart contract, which acts as a bridge between the blockchain platform and national or international renewable energy certification bodies. For instance, in Europe, GOs issued through this system could be automatically recognized by national authorities, while in the U.S., RECs, can be integrated with local market operators. This regulatory integration ensures that energy transactions conducted on our platform meet compliance requirements, enabling broader adoption by companies and organizations required to adhere to strict environmental standards.

Financial and Market Settlements: Traditional energy markets operate with financial settlement mechanisms to account for the differences in energy supply and demand, often mediated by centralized market operators. Our system complements this by automating the financial settlements for energy contracts using smart contracts. The pricing and settlement terms defined in VPPAs are enforced by the blockchain, and the integration of cryptocurrencies or tokenized assets can streamline the financial flow between producers and buyers. These contracts can be further integrated with existing financial clearinghouses and energy market exchanges to handle fiat currency settlements when necessary.

Market Expansion through Decentralized Participation: Traditional energy markets are often limited by centralized gatekeepers, which can restrict participation to large, established producers and buyers. Our blockchain-based platform opens up the market to smaller participants, such as community solar projects, individual producers, or small businesses that want to buy or sell renewable energy. By using decentralized technology, smaller entities can interact directly with one another without the need for intermediaries, allowing for a more inclusive and accessible energy market.

5.3.2 Expanding the Scope of Integration

Cross-Border Energy Trading: One significant benefit of using blockchain technology is the potential for cross-border energy trading, which is often challenging in traditional markets due to regulatory differences and inefficiencies in managing international contracts. Through VPPAs on our platform, producers and buyers from different countries can enter into legally binding agreements. The use of globally recognized EACs, such as iRECs, ensures that renewable energy certificates are recognized across borders, allowing for smooth international trading. Additionally, blockchain's decentralized nature makes it easier to manage and enforce these contracts across different regulatory landscapes.

Integration with Emerging Technologies: As energy systems evolve with advancements such as smart grids, IoT devices, and AI-based demand forecasting, our blockchain-based energy trading platform can serve as a foundational layer that integrates these emerging technologies. Smart grids, for instance, can automatically report energy production and consumption data to the blockchain in real time, enhancing the accuracy and timeliness of energy transactions. IoT devices, installed at the energy production or consumption points, can serve as oracles that feed verified data into the blockchain, ensuring the accuracy of energy transactions. These integrations can further automate and optimize energy trading, enabling more efficient energy use across the grid.

Carbon Accounting and Sustainability Reporting: Companies are increasingly required to account for their carbon emissions as part of their sustainability strategies. Integrating our blockchain platform with existing carbon accounting systems offers the potential for automated tracking of carbon credits or offsets associated with energy use. As companies use renewable energy verified through EACs, their blockchain-based energy consumption data can feed directly into their carbon accounting reports. This automated reporting can simplify the process of demonstrating compliance with environmental standards such as the Greenhouse Gas Protocol or participation in voluntary initiatives such as RE100.

5.4 Security and Scalability Considerations

Security and scalability are two critical considerations for any blockchain-based energy trading system aiming to become a commercially viable solution. In the context of this project, which focuses on facilitating VPPAs, these considerations are even more significant. The complex nature of energy markets, combined with the technical challenges of blockchain technology, presents various difficulties that need to be addressed to ensure a robust, efficient, and secure platform.

From a security perspective, the inherent risks associated with smart contract vulnerabilities must be carefully mitigated. Smart contracts, while providing automation and transparency, are vulnerable to several types of attacks, such as reentrancy, overflow/underflow bugs, and unauthorized access. In our system, these contracts handle sensitive data related to energy pricing, transactions, and corporate agreements. Any breach could result in significant financial loss or system disruption. To mitigate these risks, the use of established libraries like OpenZeppelin for secure mathematical operations, combined with access control mechanisms such as the `onlyRegisteredProducers` modifier, ensures that only authorized entities can interact with critical contract functions. Additionally, regular security audits and the use of automated security testing tools like MythX or Slither are essential for maintaining the integrity of the contracts over time.

Another important aspect of security is the reliability of oracles, which provide off-chain data to smart contracts. Inaccurate data from compromised oracles could lead to the incorrect execution of contracts, potentially affecting energy trading outcomes. A decentralized approach to oracles, using systems like Chainlink, can help ensure data accuracy by reducing the risk of a single point of failure. Moreover, incorporating validation mechanisms to cross-verify data from multiple sources before it is accepted on-chain further enhances data integrity. Additionally, the optimistic rollup model introduces a challenge period where transactions can be disputed if found fraudulent, but this introduces a potential window for attackers to exploit. The system relies on a robust incentive structure to discourage fraudulent behavior, where verifiers risk losing their staked funds for verifying invalid transactions, thereby promoting honest participation.

Key management also presents significant security risks. In blockchain systems, private keys serve as the primary means of accessing funds and executing contracts. Poor key management, such as storing keys insecurely or exposing them to malicious software, can result in unauthorized access or theft. For a commercial energy trading system, proper key management protocols, such as using hardware wallets and multi-signature wallets for large transactions, are essential. Regulatory compliance further complicates security considerations. Blockchain-based systems, particularly those dealing with energy and finance, must navigate a complex web of legal requirements, including energy trading regulations, financial laws, and data privacy standards. Ensuring that smart contracts comply with these regulations, while still providing a decentralized and efficient trading platform, requires collaboration with legal experts and a clear understanding of jurisdictional requirements.

Scalability is another significant challenge. As the number of participants in the platform grows, so too will the volume of transactions. Layer-1 blockchain networks, such as Ethereum, are limited by throughput, leading to congestion and high transaction costs, which can deter widespread adoption. This project addresses these limitations by utilizing a Layer-2 solution, specifically Optimistic Ethereum. Optimistic rollups enable the system to offload most of the transaction processing to off-chain environments, reducing the computational burden on the main chain while maintaining security through periodic checkpoints on Ethereum. This approach significantly lowers transaction costs and increases throughput, allowing the platform to scale without sacrificing security. However, this model introduces finality delays due to the dispute resolution period, which can be up to seven days. While necessary for fraud prevention, this delay may complicate time-sensitive agreements, such as energy trades. Clear contractual terms regarding delivery timelines and payment settlements must account for this delay, particularly for high-value transactions.

In addition to transaction throughput, gas costs present another scalability issue. On Ethereum's Layer-1, gas fees can fluctuate dramatically based on network congestion, making it expensive for smaller energy producers and buyers to interact with smart contracts. By leveraging Layer-2 solutions, the platform reduces these costs, although periodic interactions with the main Ethereum network for final settlement will still incur some gas fees. Optimizing contract design to minimize unnecessary state changes and maximize efficiency will further help reduce costs [51]. Another scalability concern is data storage. Blockchain networks are not designed to handle large amounts of data efficiently, and storing detailed energy production and consumption data directly on-chain would be both expensive and impractical. Instead, a hybrid approach is used, with critical contract execution data stored on-chain, while non-critical data, such as detailed energy consumption records, is stored off-chain using decentralized storage solutions like IPFS [36].

As the project transitions from a proof-of-concept to a commercial product, user onboarding and adoption become crucial for scaling. Many potential users in the energy market may be unfamiliar with blockchain technology, and integrating a decentralized system into their existing infrastructure could be challenging. User-friendly interfaces, such as MetaMask for wallet management and Web3.js for blockchain interaction, are critical to ensuring that the platform is accessible to both technical and non-technical users. Additionally, for larger enterprises, API integrations with existing Energy Management Systems (EMS) can provide a seamless user experience, allowing them to leverage the benefits of blockchain without overhauling their current operations.

Despite these scalability improvements, there are inherent challenges in commercializing blockchain-based energy solutions. The energy sector operates under highly specific regulatory frameworks that vary across regions, complicating the implementation of a global blockchain solution. The lack of standardization in energy certifications and trading practices means that the system must be adaptable to different jurisdictions. Furthermore, the high initial costs of deploying and maintaining blockchain infrastructure, combined with the need for regulatory approval, may delay adoption by large energy companies [52].

5.5 Cost-Benefit Analysis

The cost-benefit analysis (CBA) of implementing VPPAs on the Optimistic Ethereum blockchain is essential to understanding the economic feasibility of deploying smart contracts at scale. This analysis considers the variables that impact both costs and benefits, focusing on gas fees, scalability improvements, transaction efficiency, and the economic gains from utilizing a decentralized platform for energy trading.

To perform this analysis, we will calculate the gas costs associated with executing smart contracts and compare these to the potential benefits in terms of reduced transaction costs, increased transparency, and improved security in energy trading. We will also look at the potential savings for energy producers and buyers due to automation and reduced intermediaries in the energy market.

Variables and Gas Costs

The cost of deploying and interacting with smart contracts on the blockchain is directly proportional to the gas consumed by the execution of contract functions. On Optimistic Ethereum, gas costs are significantly lower than on Ethereum's Layer 1 network, thanks to off-chain computation and periodic rollups for settlement [31], [34], [35], [37], [51].

Key variables to consider in calculating costs include:

- **Transaction Type** (e.g., contract creation, registration, trading, claiming)
- **Function Complexity** (e.g., computational complexity of each smart contract function)
- **Gas Price** (determined by the network at the time of transaction)
- **Gas Limit** (the maximum amount of gas that a transaction can consume)
- **Average Gas Fee** (measured in gwei)

We use the following mathematical formula to estimate gas costs on Ethereum:

$$Total\ Cost\ (in\ ETH) = Gas_{Used} \times Gas_{Price}$$

Where:

- **Gas Used** refers to the actual amount of gas consumed by the transaction.
- **Gas Price** is the price of gas in gwei, which fluctuates based on network congestion.
- 1 gwei = 10^{-9} ETH.

Transactions on Layer 2 networks follow a different fee structure compared to those on Layer 1. For Optimism, transaction fees consist of two main components: 1) **Rollup Costs**, which cover the expense of bundling transactions into batches and submitting them to Ethereum (Layer 1), and

2) **L2 Execution Costs**, which are the fees for processing the transaction directly on Optimism (Layer 2).

The following mathematical formula calculate transaction costs:

$$OP\ Tx\ Fee = [Fee_{Scalar} \times L1_{GasPrice} \times (Calldata + Fixed\ Overhead)] + \{L2_{GasPrice} \times L2_{GasUsed}\}$$

On Optimism, instead of paying full Layer 1 Ethereum gas fees for the entire transaction, you only pay Layer 1 gas fees for a small portion that needs to be posted to Ethereum in a transaction batch (L1 Gas Used). The actual execution of the transaction occurs on Optimism (Layer 2). Optimism uses the same amount of gas as the transaction would require on Ethereum (Gas Used if on Ethereum), but the gas price on Optimism is significantly lower—just 0.001 gwei—making it far cheaper than Layer 1.

5.5.1 Gas Costs in Optimistic Ethereum

Optimistic Ethereum uses optimistic rollups, which offload most of the computation off-chain and only submit batched transactions to Ethereum's Layer 1 for final settlement. This allows for lower gas fees compared to Ethereum mainnet. However, periodic interactions with the main Ethereum network (e.g., for finalizing transactions) still incur Layer 1 gas costs.

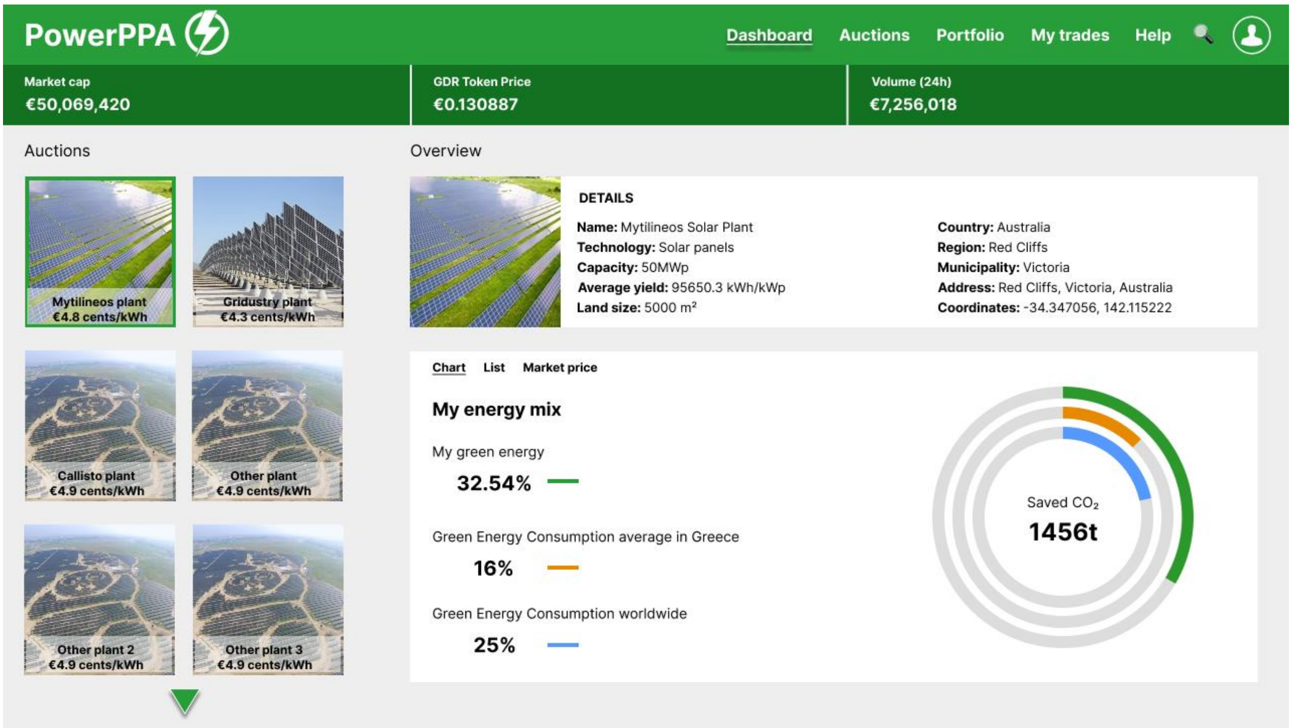
Table 4: Gas costs in Ethereum vs Optimistic Ethereum Blockchain.

TRANSACTION	GAS COST (OPTIMISTIC)	GAS COST (ETHEREUM L1)	SAVINGS
CONTRACT DEPLOYMENT	200,000 gas	1,500,000 gas	~85%
FUNCTION EXECUTION	50,000 gas	300,000 gas	~83%
PPA CREATION (CORPORATE)	120,000 gas	500,000 gas	~76%
PPA CLAIM	80,000 gas	250,000 gas	~68%

Table 4 illustrate that Optimistic Ethereum offers a substantial reduction in gas costs due to the off-chain execution of most transactions. The main expense lies in the final verification and settlement on Ethereum's Layer 1, which still incurs higher fees.

Chapter 6: User Interface (UI) Development

The PowerPPA platform is designed to provide a seamless user experience for energy producers and buyers within the energy trading ecosystem. Built using React JS, the platform is part of a broader initiative named Gridustry, launched in 2021, focusing on blockchain technology in the energy sector. The platform was developed in collaboration with the Applied Research and Development (R&D) division of Protergia, Greece's largest private electricity company, to revolutionize the way energy is traded, particularly through PPAs.



Market cap
€50,069,420

GDR Token Price
€0.130887

Volume (24h)
€7,256,018

Mytilineos plant
€4.8 cents/kWh

Gridustry plant
€4.3 cents/kWh

Callisto plant
€4.9 cents/kWh

Other plant
€4.9 cents/kWh

Other plant 2
€4.9 cents/kWh

Other plant 3
€4.9 cents/kWh

DETAILS

Name: Mytilineos Solar Plant
Technology: Solar panels
Capacity: 50MWp
Average yield: 95650.3 kWh/kWp
Land size: 5000 m²

Country: Australia
Region: Red Cliffs
Municipality: Victoria
Address: Red Cliffs, Victoria, Australia
Coordinates: -34.347056, 142.115222

My energy mix

My green energy
32.54%

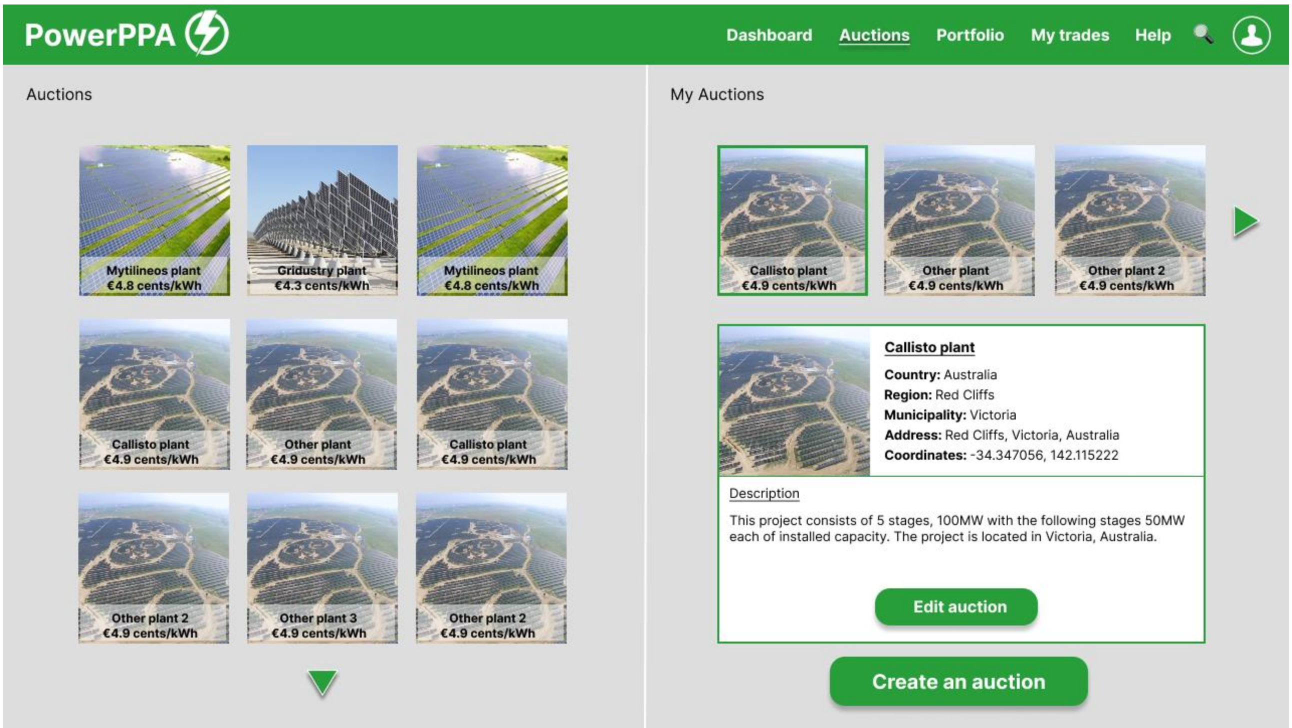
Green Energy Consumption average in Greece
16%

Green Energy Consumption worldwide
25%

Saved CO_2
1456t

Figure 12: Dashboard of the platform designed for PoC.

The platform offers a comprehensive auction system where energy producers can create new auctions for their energy production capacity. The auction creation process is streamlined, guiding users step-by-step through the input of essential details such as plant capacity, location, price per kWh, and PPA duration. Additionally, producers are required to upload documentation to ensure the validity of their auction, which is automatically processed by the platform's validation system.



Callisto plant

Country: Australia
Region: Red Cliffs
Municipality: Victoria
Address: Red Cliffs, Victoria, Australia
Coordinates: -34.347056, 142.115222

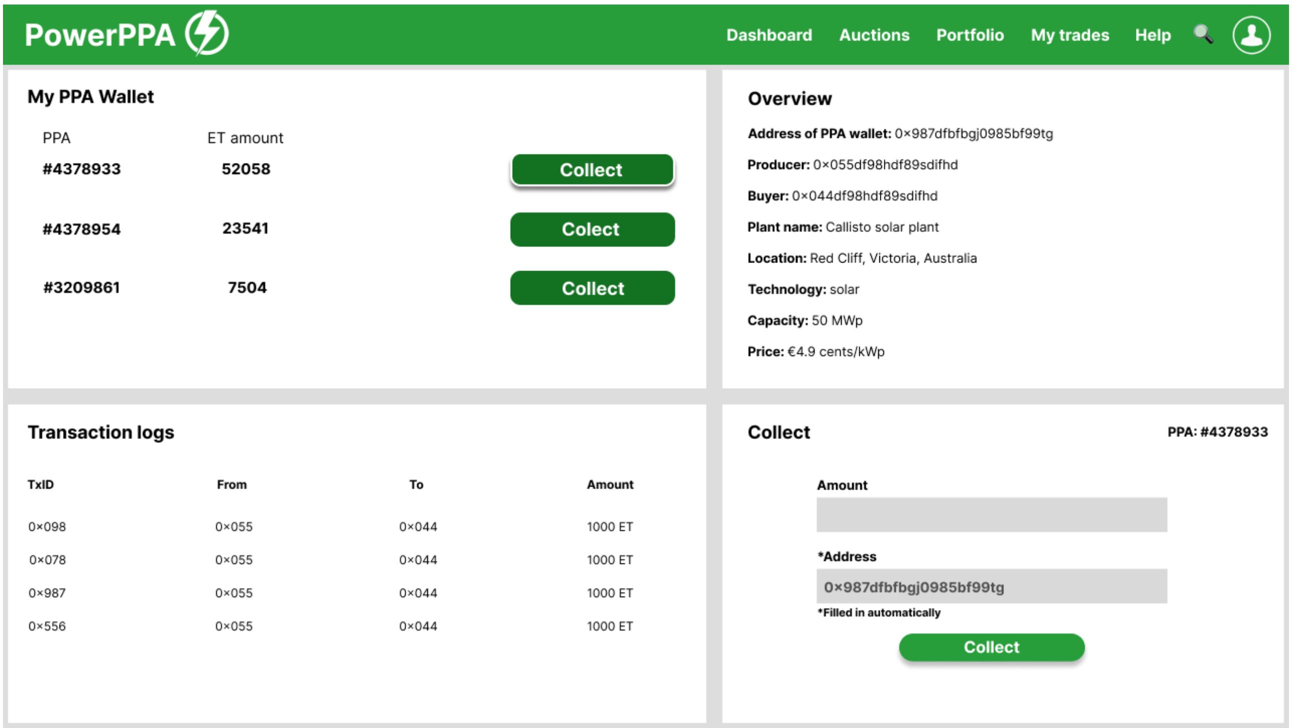
Description

This project consists of 5 stages, 100MW with the following stages 50MW each of installed capacity. The project is located in Victoria, Australia.

Figure 13: This image illustrates the available auctions and the active auctions of the producer.

The marketplace ensures that users have all the necessary information to make informed decisions, including current market prices, average energy yields, and plant capacity. Buyers can also set the amount of energy they wish to purchase and the price they are willing to pay, fostering a competitive and transparent energy market.

Once auctions are submitted by energy producers, the platform incorporates a robust validation process to ensure that all required documents are in place and that the auction meets the necessary criteria before being made available for bidding. After validation, auctions are published, and producers are notified. Buyers and sellers are kept informed through a notification system, streamlining communication and ensuring transparency throughout the process.



My PPA Wallet

PPA	ET amount
#4378933	52058
#4378954	23541
#3209861	7504

Overview

Address of PPA wallet: 0×987dfbfbgj0985bf99tg
Producer: 0×055df98hdf89sdifhd
Buyer: 0×044df98hdf89sdifhd
Plant name: Callisto solar plant
Location: Red Cliff, Victoria, Australia
Technology: solar
Capacity: 50 MWp
Price: €4.9 cents/kWp

Transaction logs

TxID	From	To	Amount
0×098	0×055	0×044	1000 ET
0×078	0×055	0×044	1000 ET
0×987	0×055	0×044	1000 ET
0×556	0×055	0×044	1000 ET

Collect **PPA: #4378933**

Amount

***Address**
0×987dfbfbgj0985bf99tg
***Filled in automatically**

Figure 14: The wallet page to collect the issued EACs from active PPAs.

The platform also includes portfolio management functionality, where users can track their energy assets, monitor the percentage of green energy they are consuming, and review their transaction history. This feature allows both producers and buyers to have a comprehensive overview of their energy activities and investments, facilitating more informed decision-making and promoting the adoption of renewable energy.

Chapter 7: Evaluation of Implementation and Results

In this section, we evaluate the implementation of our platform, focusing on how the use of Optimistic Ethereum Blockchain Network optimizes VPPAs and addresses some of the fundamental issues observed in traditional PPA models. The adoption of blockchain technology, specifically Optimistic Ethereum, ensures that key processes such as contract creation, validation, and energy transaction settlements are secure, scalable, and cost-efficient. At the same time, our solution provides a decentralized marketplace where energy buyers and producers (sellers) can trade energy contracts transparently, solving some of the limitations that plague traditional PPA frameworks.

7.1 Optimization of PPAs with Blockchain Integration

Traditional PPAs, as highlighted in Figure 1, face several significant challenges: high legal and financial transaction costs, lack of liquidity, single counterparty risk, and an exclusion of small buyers due to the large volumes typically required. Our blockchain-based platform directly addresses these inefficiencies by automating energy contract creation through smart contracts, enabling fractional contracting, and introducing market liquidity through a decentralized platform. By using the Optimistic Ethereum network, we can reduce transaction costs and increase transaction throughput without sacrificing security, which is crucial for energy trading.

The implementation of VPPAs through our smart contracts offers a number of benefits. Energy buyers and sellers can now establish agreements with predefined terms or, alternatively, participate in auctions to determine the most competitive pricing. Moreover, our platform supports fractional contracting, allowing smaller buyers to aggregate their demands into a larger purchasing block. This enables more inclusive participation in renewable energy markets, where traditionally, only large corporations could engage.

Table 1 below illustrates a cost comparison between a traditional PPA and a VPPA conducted through our platform on the Optimistic Ethereum blockchain. As seen, the elimination of intermediary costs and reduced transaction times contribute to substantial financial savings.

Table 5: Key differences of Traditional PPAs and Optimized PPAs using Blockchain and VPPAs.

Metric	Traditional PPA	Optimized VPPA
Legal & Financial Costs	~$1M per client maybe more	costs can be reduced by around **80%**
Contract Duration (months)	12-18	few months, depends on the auction
Buyer Access	Only large buyers	Small & large buyers
Liquidity	Low (Single buyer)	High (Multiple buyers/sellers)

Traditional PPA:

- The setup of a traditional PPA involves complex, time-consuming negotiations between multiple stakeholders, including legal teams, financial institutions, energy producers, and buyers. This process often takes **12-18 months**. The long duration is attributed to the need for:
    - Extensive negotiations of terms and conditions.
    - Legal vetting and risk assessments.
    - Energy regulatory compliance.
    - Due diligence on project financing and creditworthiness of counterparties.

- Industry benchmarks, such as those provided by renewable energy consulting firms and PPA service providers, support this timeline for the typical end-to-end lifecycle of PPA creation.

Blockchain-Optimized VPPA:

- By contrast, the use of **smart contracts** significantly reduces the contract creation timeline. Since the smart contract logic is predefined and automatically executed based on certain triggers (like energy production, agreed-upon terms, pricing), many of the manual processes are bypassed.
- A VPPA setup on a blockchain platform like **Optimistic Ethereum** can reduce the time to contract creation. This reduction in comes from:
    - The use of decentralized auctions where buyers and sellers match instantly based on predefined criteria (such as the lowest energy price).
    - Automatic validation of participants through blockchain identities and predefined logic.
    - No need for lengthy negotiations, since smart contracts codify the terms in advance, and the blockchain ensures trust without a third party.

7.2 Green Energy Certification

An essential feature of our platform is the integration of a green energy certification system. We have developed a token that represents Green Energy Certificates, such as GOs, which are used in Europe to certify renewable energy production. This token provides transparency and traceability in energy consumption, ensuring that energy purchased through the platform is genuinely green. However, it is important to note that this token serves solely for certification purposes and is not a financial instrument. Its role is to track the origin and ownership of energy, enhancing trust in the system.

7.2.1 Constraints and Issues for Production-Level Use

While the implementation of our platform demonstrates the benefits of using blockchain for energy trading, there are several constraints and considerations for deploying such a solution at a production level.

Scalability: Although Optimistic Ethereum offers better scalability than traditional Ethereum networks, large-scale energy markets with high-frequency transactions could still face bottlenecks. This could be mitigated by layer-2 scaling solutions or additional optimizations in the smart contracts.

Regulatory Challenges: Different countries have varied regulations surrounding energy trading, and a decentralized platform might face legal barriers in certain jurisdictions. A production-level platform would need to ensure compliance with local regulations, which could require significant customization.

Security Considerations: While blockchain is inherently secure, smart contracts are vulnerable to bugs and exploits. Therefore, any production-level platform must undergo rigorous security audits to prevent financial loss or system manipulation. Implementing insurance mechanisms or trusted validators might also be necessary.

Energy Market Volatility: The energy market is subject to fluctuations due to external factors like weather conditions and geopolitical events. Smart contracts must incorporate mechanisms for renegotiation and contract adjustment to account for this volatility, ensuring long-term price stability for both buyers and sellers.

User Adoption and Education: The success of any blockchain-based platform relies heavily on user adoption. Energy market participants, including small buyers and sellers, may not be familiar with blockchain technology or its benefits. Thus, educational resources and user-friendly interfaces are crucial for fostering trust and encouraging participation.

7.3 Conclusion

In this Diploma Thesis, we explored the development and implementation of a blockchain-based platform aimed at facilitating decentralized energy trading through VPPAs. The central focus of the project was the application of **Optimistic Ethereum** to enhance scalability and reduce transaction costs, which are traditionally significant barriers in blockchain systems. Through this platform, we demonstrated how smart contracts can automate energy trading while maintaining transparency, immutability, and trust between participants, without the need for some intermediaries.

The **Optimistic Ethereum network** was chosen as it offers a layer 2 solution to Ethereum's scalability challenges, allowing transactions to be processed off-chain and settled on-chain. This greatly reduces gas fees and enhances transaction throughput. However, it should be noted that while this approach significantly improves performance compared to Layer 1 Ethereum, **scalability limitations** remain, particularly as transaction volumes grow. Further optimizations, both at the contract and network levels, will be necessary to scale the system to a global marketplace.
From a **security perspective**, the project implemented several best practices to ensure the robustness of the smart contracts. We followed rigorous auditing processes and utilized automated tools, such as Slither, to detect potential vulnerabilities in the codebase. It is important to acknowledge that **smart contracts** and this project as a whole, are just pilot work and not a complete solution and the potential for unforeseen security risks remains. As demonstrated in previous high-profile security breaches in blockchain systems, smart contracts must continuously evolve to address new threats.

The **PowerPPA platform** successfully automated the creation, management, and execution of VPPAs between energy producers and buyers. By integrating an auction mechanism, the platform provided a more competitive and dynamic energy market, where participants can bid for energy at real-time prices. This process reduces the costs and administrative burden typically associated with traditional PPAs, while enabling smaller buyers and sellers to participate in renewable energy trading.

Despite these advancements, the platform still faces challenges in moving from a **proof-of-concept** to a fully operational system at a **production level**. **Regulatory compliance** remains a significant hurdle, as energy markets are highly regulated and vary across regions. Future iterations of the platform will need to incorporate region-specific legal frameworks to ensure compliance, especially when scaling internationally. Additionally, while the Optimistic Ethereum network offers a solution to gas fees, further optimizations will be required to address the challenges of increasing network congestion.

In conclusion, this project highlights the potential of blockchain technology to transform the energy sector by creating more transparent, decentralized, and efficient energy markets. The **PowerPPA platform** has demonstrated how the use of smart contracts, coupled with layer 2 scalability solutions, can reduce costs and enhance accessibility for all participants in the energy market. Moving forward, ongoing improvements in security, scalability, and regulatory integration will be critical to realizing the full potential of this technology.

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Abbreviations - Initialisms - Acronyms

PPA	Power Purchase Agreement
VPPA	Virtual Power Purchase Agreement
DApp	Decentralized Application
ERC	Ethereum Request for Comments
EAC	Energy Attribute Certificates
GOs	Guarantees of Origin
REC	Renewable Energy Certificate
I-REC	International Renewable Energy Certificate
L1	Layer 1 (Main blockchain layer)
L2	Layer 2 (Secondary layer for scalability solutions)
PoS	Proof of Stake
TPS	Transactions per Second
EVM	Ethereum Virtual Machine
ETH	Ether (the cryptocurrency used on Ethereum)
RE100	A global initiative committed to 100% renewable energy
RES	Renewable Energy Sources
MWh	Megawatt-Hour
GHG	Greenhouse Gas
EECS	European Energy Certificate System
REGO	Renewable Energy Guarantees of Origin
TIGRs	Tradeable Instruments for Global Renewables
CSRD	Corporate Sustainability Reporting Directive
NFTs	non-fungible tokens
TXs	transactions
REGO	Renewable Energy Guarantees of Origin
PoW	Proof of Work
ABI	Application Binary Interface
EMS	Energy Management Systems
CBA	Cost-Benefit Analysis
VPP	Virtual Power Plant
P2P	Peer to Peer
IoT	Internet of Things
DER	Distributed Energy Source
DSO	Distribution System Operators
Gas Fees	The cost paid by users to perform transactions on the Ethereum network, calculated in gas (a unit of computational work)

Fraud Proofs	A security mechanism used in optimistic rollups where transactions are assumed valid unless a fraud proof is provided to dispute them
Gas Limit	The maximum amount of gas a transaction can consume on the Ethereum network
Gwei	A small denomination of Ether, used to measure gas fees (1 Gwei = 0.000000001 ETH)