Master of Science

Sustainable Management and Technology

HEC – University of Lausanne
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WORKING DRAFT

Decentralizing Carbon Accountability

A Platform for User-Centric Blockchain Emissions Estimation and Offset

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MASTER THESIS

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Executive summary

Abstract

Put abstract in e4s template

Is this too long?

Executive summary. The advent of blockchain technology has raised concerns about its high energy use and carbon emissions. This is partly due to the current dominance of proof-of-work-driven Bitcoin, the first network to gain widespread adoption and media coverage. However, different consensus mechanisms and design choices result in varying environmental footprints across blockchains. While the recent release of the first industry blockchain Environmental Social & Governances (ESGs) benchmark enables standardized comparisons between chains at an aggregate level, a granular methodology for user-level emissions accounting is lacking. ESG

This thesis introduces an attribution model designed to map the carbon footprint of blockchain at a user-responsibility level. Novel to this research is the attempt to weigh responsibility factors based on the principle of proportional benefits. This approach exploits the inherent transparency of blockchain data to capture the relative value, specific to each network, that users place on different blockchain functionalities. We find that two generalizable categories of benefits emerge: the Transactional use case (benefits from active transacting or interacting) and the Asset-Securing use case (benefits from passively holding or securing assets). Key parameters such as asset balance, signed transactions, and gas expenditure are used as representative indicators of benefiting from a network use case. This methodology allocates the overall chain emissions to specific users based on their interaction patterns. The evolutions of network-specific transaction fees and market capitalization are used to derive weight for these parameters.

Unsure. Is the part clear?

Furthermore, a proof-of-concept tool (GreenBlocks) is built to showcase the attribution model, allowing users to estimate and offset their emissions through carbon credits. Based on the Ledger Live platform, this platform interacts seamlessly with leading blockchains and links with on-chain carbon market partners to retire offsets with maximal transparency.

Greenblocks provides transparent and personalized insights into blockchain emissions for end-users. By linking usage to quantified environmental impact, it promotes awareness. It enables offsets as a means for users to bear the actual costs behind the benefits they reap from using the technology. Moreover, it demonstrates the potential for on-chain data to be used as the foundation for an appropriately nuanced attribution of external costs in a system. Moving past rudimentary address metrics, more complex behaviors and benefits can be modeled, enabling the distribution of externalities like a Pigouvian tax. Thus, this thesis proposes a bottom-up, user-focused approach to align blockchain adoption with environmental sustainability. This is achieved by pioneering user-level footprint attribution, arising from the *Benefiiciary pays principle.*

Add section on further opportunities for the blockchain-sustainability space

Acknowledgements

Contents

Chapter 1

Introduction

1.1 Background and Motivation

Compartiment in subsections to improve narrative flow

Origins, promise and challenges of blockchain technology

The advent of blockchain technology since the launch of Bitcoin in 2009 has sparked a revolution in systems of value transfer, transparency, and decentralization [1]. However, the early meteoric rise of cryptocurrencies and underlying blockchain networks has raised critical concerns regarding their environmental sustainability. With the benefit of hindsight, we can view this period as Gartner's Peak of Inflated Expectations. Now, with notorious founders imprisoned, increasing regulatory scrutiny, and the total cryptocurrency market capitalization down XX% from its peak , the blockchain ecosystem stands at a crossroads. This is an opportunity to refocus on the core propositions of blockchain technology and ensure its long-term viability.

cite

The dominant network, Bitcoin, which utilizes a computationally-intensive proof-of-work consensus mechanism, has attracted particular scrutiny for its high energy consumption. Recent estimates indicate the Bitcoin network alone may consume between 115 and 150 TWh annually, comparable to entire countries like the Netherlands [2, 3]. This growing apetite for energy competes with the just starting energy transition, putting electrical production and distribution networks under stress. Finally it also results in significant CO2 emissions, hardly compatible with global climate goals like the Paris Climate Accords.

Limitations of current approaches

However, we must recognize the complexity and nuance when evaluating blockchain sustainability. Consensus protocols, design choices, and use cases vary greatly across different networks, leading to wide variability in energy needs and emissions. For instance, proof-of-stake networks like Cardano and Solana promise energy savings by factors of 1000x or more compared to proof-of-work [4]. Moreover, Ethereum recently completed its highly anticipated, technically and politically complex transition from proof-of-work to proof-of-stake, demonstrating that such migrations are viable for major networks. [5] The nascent field of blockchain sustainability analysis must evolve more granular, differentiated perspectives.

Initial responses from the blockchain industry have focused on high-level aggregate comparisons and rankings between networks. For example, recent benchmarks like the Crypto Carbon Ratings Institute methodology provide standardized comparisons of the total life-cycle emissions across chains [5]. However, these overlook the diversity of users and fail to provide accountability at an individual level.

This poses a critical gap, especially as blockchain technology expands into mainstream adoption. We lack a methodology to attribute network-wide emissions to specific users based on their unique activity patterns and values. Such granular carbon accounting can raise awareness of individual impact and empower ethical participation.

Opportunities for user-level footprinting

To address this, the novel approach in this thesis involves an attribution model that weighs factors like asset holdings, transactions, and computations based on their estimated importance to users on each chain. By considering relative user perspectives, we can map emissions more accurately to individual entities like protocols, DAOs, or end-users. This unconventional yet powerful approach unlocks new potentials for transparency, responsibility, and sustainability.

1.2 Problem Statement

As blockchain technology progresses into mainstream integration, the lack of transparency and accountability for emissions at an individual user level poses a critical gap. For example, retail investors drawn to crypto assets may be unaware of the passive environmental impacts associated with their portfolios over time. There is also increasing offering of decentralized applications (web3) with usage beyond those of investing. Granular carbon accounting and attribution to individual wallets can raise awareness and enable offsetting as a means for users to take responsibility of their actions.

Moreover, this gap becomes even more complex for providers of decentralized apps or decentralized autonomous organizations (DAOs) comprising multiple smart contracts and user addresses. Without a methodology for attributing network-wide emissions based on collective usage patterns, a DAO cannot fully assess and mitigate its overall carbon footprint.

Therefore, the overarching problem this thesis addresses is:

"How can we design an attribution model that allocates the carbon emissions of any blockchain network to specific user entities or addresses in a transparent, accurate, and relevant manner based on their unique activity patterns?"

1.3 Research Questions and Ojbectives

To systematically address the problem of transparent and accurate carbon attribution for blockchain users and entities, this thesis pursues four key research questions:

1. How can blockchain emission factors be quantified at a granular, user-centric level, beyond aggregate network-wide estimates?
2. What are appropriate metrics and weighting systems to reflect the responsibilities of diverse blockchain users based on their activities?
3. How can we validate and demonstrate such an attribution model through a practical implementation?
4. What are the broader implications of user-centric emissions accounting for accelerating sustainability as blockchain technology matures?

The main objectives of this work are:

Develop a User-Level Attribution Model
Develop a robust emissions attribution methodology based on usage and responsibility.

Greenblock: Pratical Application
Implement and validate the model through a functional proof-of-concept application.

Promote awareness and Responsibility
of environmental impact among blockchain users.

The Future of Sustainability and Blockchain

to complete

1.4 Scope and Limitations

TO COMPLETE

1.5 Structure of the Thesis

TO COMPLETE

Chapter 2

Litterature Review

2.1 Economic Externalities

2.2 Evolution of Blockchain Technology

2.3 Environmental Impact of Blockchains

2.3.1 Energy Consumption and Related Emissions

2.3.2 Current Measurement Methodologies and Datasets

2.4 User-Level Emissions Attribution

Chapter 3

Methodology: User-Level Emissions Attribution Model

3.1 Overview

Find where to include steps of the work. Interviews and data collection

As blockchain technology expands onto more use cases and scale in it adoption, quantifying and attributing associated carbon emissions transparently emerges as a valid need. While aggregate estimates provide high-level network overviews, they fail to offer accountability at an individual user level, posing a user education gap and potentially a product need.

This chapter introduces a novel methodology to attribute network emissions to specific blockchain addresses based on proportional benefits gained by users. By mapping network footprints to end-users, protocols, and DAOs, this framework enables entities to understand, report, and take action based on their responsibility in the overall emissions.

The methodology is underpinned by ethical and economic theories suggesting emissions be allocated based on the proportional benefits users derive, both actively through transferring value and interacting, and passively from securing assets. Historical trends in activity metrics like fees and market value provide useful signals into evolving blockchain utility dynamics and user perceptions of value.

By incorporating these perspectives, the model aims for a fair, customizable attribution aligned with the real-world value users obtain from blockchain networks. The following sections detail this approach and rationale.

3.2 Background - Emission attribution considerations

3.2.1 Blockchain Typology

Blockchains can be categorized into two main types based on their primary function and underlying mechanics:

this separation is also justified by the polluter and beneficiary pays framework. The limited ressource (blockspace) is shared differently for bitcoin and ethereum

Value-transfer chain (VTC) Chains that focus on transferring assets between addresses (e.g. Bitcoin and derived). VTCs are focused primarily on enabling value transfers through native cryptocurrency tokens. These chains do not typically support complex smart contract functionality like GPCs or make similar functionalities unergonomic to implement. The key operational metric for VTCs is the transaction throughput, constrained by blocksize and block intervals.

General-purpose chain (GPC) Chains that allow the deployment of smart contracts and decentralized applications (dApps) in addition to value transfer (e.g. Ethereum, Cardano, Solana). On these networks, transactions and computations are quantified using a metric called gas[1]. This concept was introduced by Vitalik Buterin in Ethereum's initial whitepaper [6] as a means to disincentivize computationally intensive smart contracts that could clog the network. Gas puts a cost on network utilization for activities like executing code, storing data, or transferring tokens based on their computation complexity. This makes it more costly to interact with complex applications and prevents situations that would halt the network like an infinite loop in a smart contract.

Due to these fundamental differences, GPCs and VTCs require distinct approaches for carbon accounting. On VTCs, the limited blockspace is the bottleneck for transactions. Hence, users conducting more transactions take up a greater share of blockspace and have higher responsibility for the chain's emissions. On GPCs, gas expenditure more accurately reflects utilization and impact on the network's computation and storage load. Users spending more gas have a greater share of responsibility by consuming more of the network's resources and throughput capacity.

Existing studies have estimated blockchain emissions using aggregate network energy use or miner rewards [7, 2, 3, 8]. However, these top-down approaches fail to capture user behavior and responsibility. Our methodology addresses this limitation through a transparent attribution model tailored to GPCs and VTCs using usage factors like gas and transactions. The following sections detail this framework.

3.2.2 Attribution framework

To review!! Add share infrastructure metaphor. Introduce polluter/benef pays from the litt review.

The Need for Proportional Benefit Attribution Carbon emissions from blockchain operations should not only be tied to direct causative actions (polluter pays principle) but also to the

[1] See: https://ethereum.org/en/developers/docs/gas/

benefits derived from these actions (beneficiary pays principle). The synthesis of the polluter pays and beneficiary pays principles results in a more nuanced understanding of emission responsibility.

Transactional Activities

Direct Actions and Associated Benefits Signing transactions or spending gas actively utilizes block space, which is a limited resource. This not only results in emissions but is also a direct reflection of users seeking to derive transactional benefits from the blockchain. By engaging in these activities, users are both contributing to emissions and benefiting from the network's utility.

Beyond Transactions: Passive Utility and Continuous Benefit

While active behaviors like transactions and gas spending are evident, there exists a passive benefit that users gain simply by holding assets on the network. This benefit accrues continuously over time and is inherently dependent on the active behaviors of others. Passive holders derive benefits from the blockchain's ability to secure value, which goes beyond the direct actions of signing transactions or spending gas. This implies an added layer of responsibility that isn't captured by looking at transactions alone.

Balancing the Attribution: Weighing Active and Passive Benefits

With two distinct parameters (active transactions/gas spending and passive holding of value), there's a need to determine their respective weights in the attribution formula. The conjunction of the polluter pays and beneficiary pays principles demands an understanding of the relative utility of both active and passive benefits to users.

Deriving Weights Factors: The Role of Transaction Fees and Market Capitalization

To establish the relative importance of active versus passive benefits, historical trends of transaction fees and market capitalization serve as proxies. These indicators reflect user-perceived utility and importance of both types of benefits over time. Transaction fees offer insights into the value users associate with active transactional capabilities, while market cap reflects the trust and perceived security in the network's ability to hold value. These can be used to derive dynamic weights for the two parameters in the emission attribution formula.

On Including Passive Holdings as a Responsibility parameter

A key diffentiator is the inclusion of historical balance as a responsibility factor. Traditionally, emissions accounting ties responsibility to direct actions like executing transactions or computations. However, in blockchains, holding assets passively (function of preserv-

Add metaphore of traditionnal infrastructure. Roads and km usage vs passive benefit of the road proximity ing/securing value) also necessitates ongoing mining and transaction fees payed by transacting users, in order to preserve liquidity and value.

Put justifications in list form to emphasize each point

Specifically, continuous mining activity and block creation are critical to maintain an active market and allow holders to liquidate assets. This activity is incentivized through transaction fees. Higher fees increase miner rewards, resulting in greater security and liquidity that benefit holders.

Therefore, despite no active behavior, holding blockchain assets creates latent demand for emissions-intensive mining. Considering this relationship, the attribution model argues for allocating part of emission responsibility to asset holders, or more generally how intensively a use is using the blockchain function of securing value.

3.3 Model Components

Building on the previous overview, this section details the specific components of the emission attribution model.

3.3.1 Historical Blockchain Emissions Data

expand, explain LCA amortized emissions

The emission rate $E(\tau)$ represents the overall amount of tCO2-equivalent emissions generated by a blockchain at time τ. This is chain-specific, with data aggregated from existing studies [3, 9].

$$E(\tau) = \text{Emission rate of chain } s \text{ at time } \tau \tag{3.1}$$

Detail combination of papers and dataset access

3.3.2 User Attribution Parameters

The attribution share (S) for an address owned by a user is proportional to the measurement of two categories of behavior-benefits. Interactve behavior (I), directly responsible for a share of emissions and reaping direct benefits from the network interaction; and Passive behavior (P), indirectly accruing benefits from the network's ongoing operation.

$$S \propto (I + P) \tag{3.2}$$

Interactive behavior is measured by the share of network ressources, blockspace, allocated to the user's address for his interactions during a period. For VTCs, this is reported by the number of signed transactions, for GPCs it is the sum of gas spent in signed transaction. Passive behavior is measured by the share of the total value secured by the network owned by the user's address.

The three factors are, for an address on a given chain and at period τ:

Interactive Behavior (I)

$T(\tau) = \frac{T_{addr}(\tau)}{T_{\text{total}}(\tau)}$	Number of transactions signed by the adress as a percentage of total transactions (for VTCs).
$G(\tau) = \frac{G_{addr}(\tau)}{G_{\text{total}}(\tau)}$	Gas spent by the adress as percentage of total gas in blocks (for GPCs).

Passive Behavior P

$B(\tau) = \frac{B_a ddr(\tau)}{B_{\text{total}}(\tau)}$	Average adress Balance as a percentage of total token supply.

Thus from equation (3.2) we have the chain-specific emission attribution share for an address at period τ:

$$S(\tau) \propto \left[B(\tau) + \begin{cases} T(\tau) & \text{for VTC} \\ G(\tau) & \text{for GPC} \end{cases} \right] \tag{3.3}$$

3.3.3 Weighting factors

Introducing a second attribution parameter raises the question of how to weigh the two factors. The attribution share is proportional to the sum of the two factors, but the relative importance of each is not clear. To address this, we derive weights for each factor based on the principle of proportional benefits.

Blockchain networks and user behaviors evolve over time. As such, the relative importance users place on transactional versus asset holding utility can shift. To account for these dynamics, the weighting factors α and β are derived by analyzing historical trends in transaction fees and market capitalization. This is done for each supported chain.

Transaction Fees F : As users invest more in transaction fees, it's an indicator that they're deriving value from the active functionalities of the blockchain. A rise in these fees underscores a user trend prioritizing transactional abilities. For VTCs this is the average transaction fee per block, for GPCs it is the average gas price per block.

Market capitalization M : Indicates user trust in the blockchain as a secure store of value. Growth in market cap highlights increasing passive utility perceived by users.

Quantifying Shifts in User Priorities

By tracking the relative changes in transaction fees and market cap over time, the model adapts to users' shifting priorities. First the relative change for each metric is calculated across the emission attribution interval, limited by the granularity of historical data available.

$$\bar{\Delta F} = \frac{1}{N}\sum_{i=1}^{N}\frac{F(\tau_i) - F(\tau_{i-1})}{F(\tau_{i-1})} \tag{3.4}$$

$$\bar{\Delta M} = \frac{1}{N}\sum_{i=1}^{N}\frac{M(\tau_i) - M(\tau_{i-1})}{M(\tau_{i-1})} \tag{3.5}$$

Maybe add a figure to illustrate the concept

Where N represents the number of time intervals.

The ratio of these changes is the relative importance of transactional benefits to passive benefits. This is the basis for the attribution weights.

$$\bar{R} = \frac{\bar{\Delta F}}{\bar{\Delta M}} \tag{3.6}$$

The relationship ratio $\bar{R}$ represents the relative importance between transaction fees and market capitalization. To convert this into proportional weights summing to 1, the transformation of equation (**??**) is used.

$$\alpha = \frac{\bar{R}}{1 + \bar{R}} \tag{3.7}$$

Subsequently, β is:

$$\beta = 1 - \alpha \tag{3.8}$$

Limitations

Using average relative changes over long intervals may fail to capture more nuanced shifts in user priorities over shorter timescales. This approach also assumes user behaviors are consistent across all blockchain users, whereas in reality different segments likely have distinct preferences. These limitations are discussed further in Section 5.4.

3.3.4 Attributed Emissions

Multiplying chain emission rate (3.1) with the sum of attribution parameters (3.3) and corresponding weights (3.7) and (3.8), we get the CO2e emissions $A(\tau)$ attributed to an address on a given blockchain for the period τ general form:

$$A(\tau) = E(\tau) \times \left[\beta \cdot B(\tau) + \alpha \cdot \begin{cases} T(\tau) & \text{for VTCs} \\ G(\tau) & \text{for GPCs} \end{cases}\right] \tag{3.9}$$

$$A(\tau) = E(\tau) \times \left[\begin{cases} \beta \cdot B(\tau) + \alpha T(\tau) & \text{for VTCs} \\ \beta \cdot B(\tau) + \alpha G(\tau) & \text{for GPCs} \end{cases} \right] \tag{3.10}$$

Cumulative Emissions

The cumulative emissions $C(t)$ for a user across a collection of owned adresses S up to time τ is:

$$C(t) = \sum_{s \in S} \int_0^t A_s(\tau) d\tau \tag{3.11}$$

This aggregates the attributed emissions across chains over time. The next section details the data sources used for each model components deined in the present section.

3.4 Data Sources and Collection

3.5 Validation and Robustness Analysis

3.5.1 Approach to Validation

3.5.2 Sensitivity Analysis Design

Chapter 4

Implementation: GreenBlocks Platform

4.1 Overview

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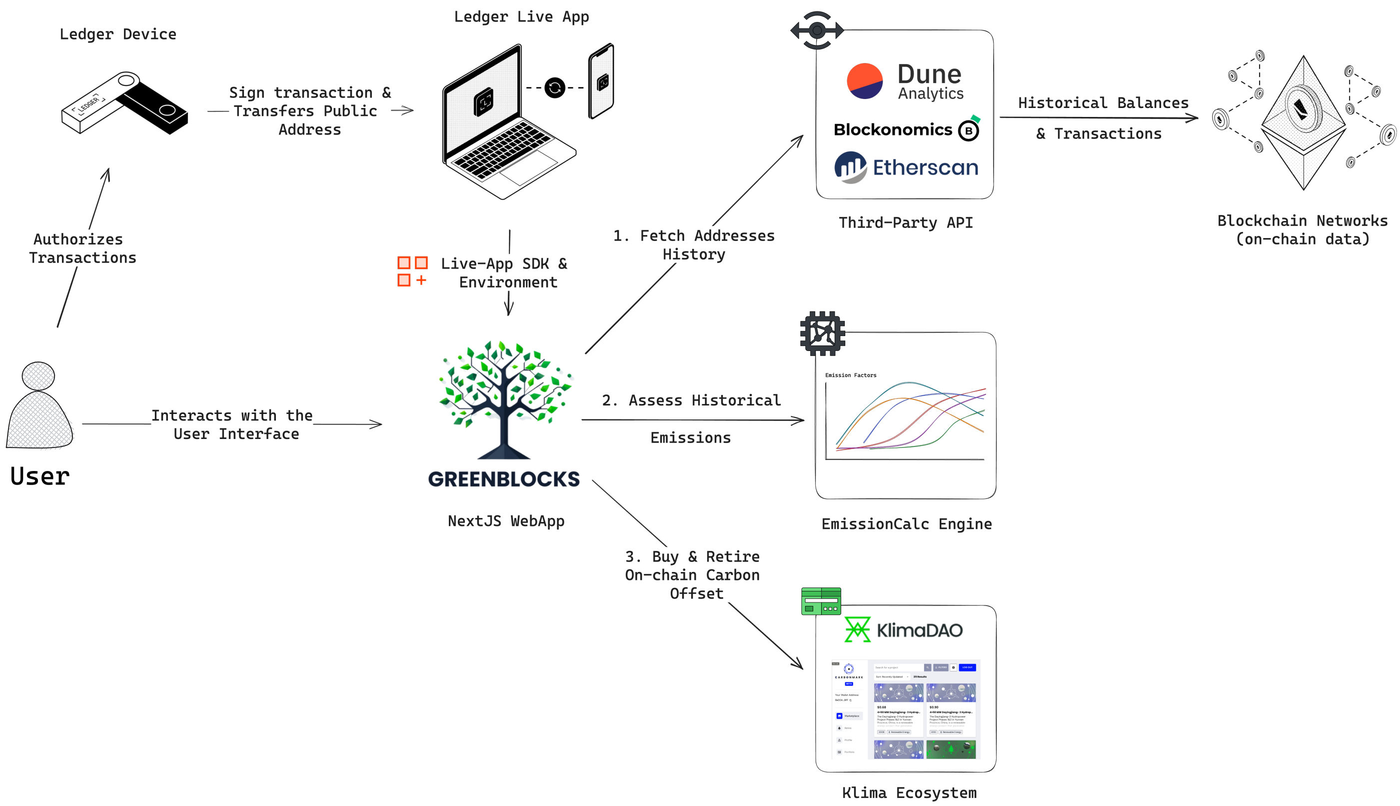

Figure 4.1: GreenBlocks - Functionnal Architecture

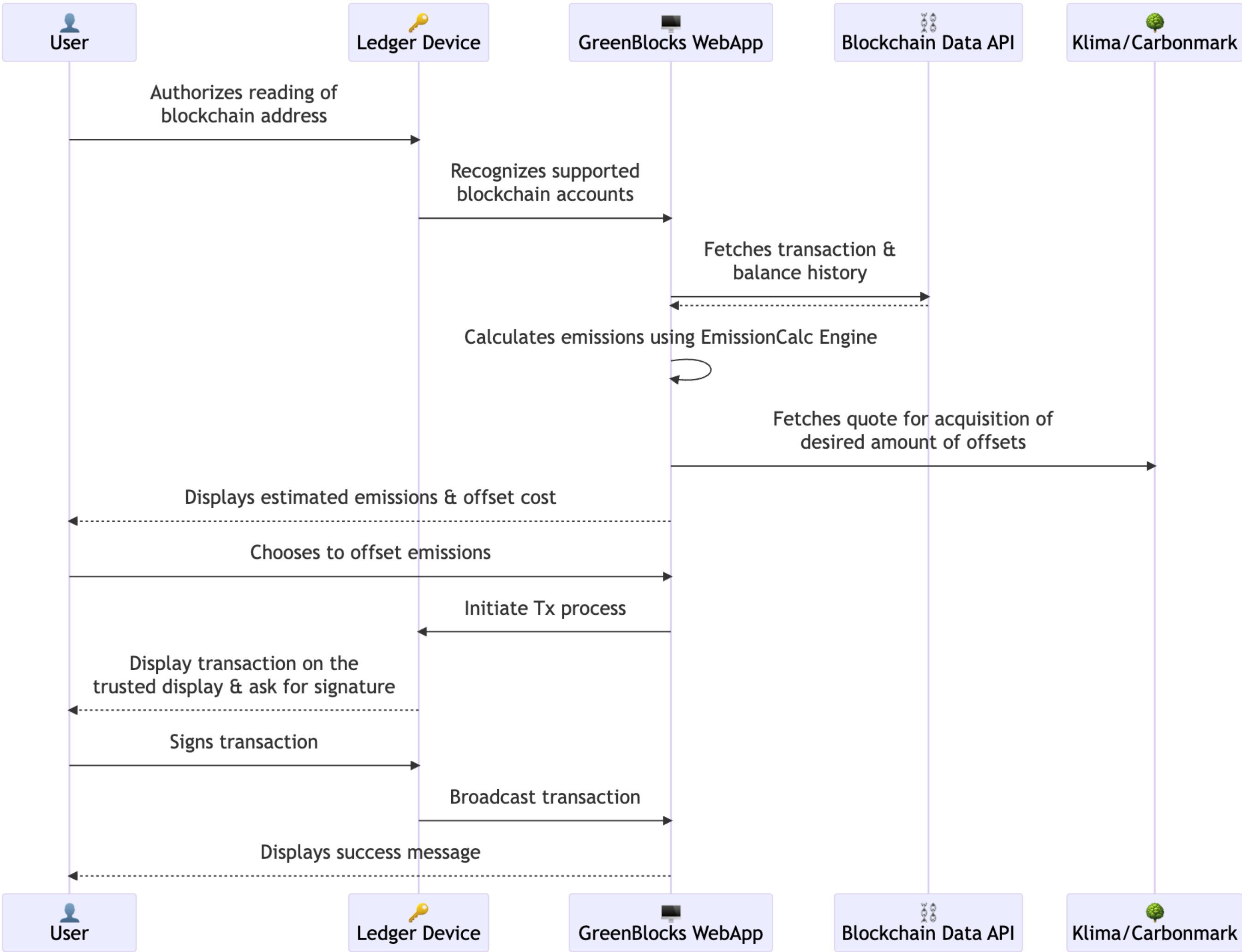

Figure 4.2: GreenBlocks - Sequence Diagram

4.2 System Architecture and Components

4.2.1 User Interface Layer

4.2.2 Middleware Layer

4.2.3 Backend Layer

4.2.4 Data Layer

4.3 Development Process

Chapter 5

Discussion

5.1 Results and Analysis

5.2 Comparative Analysis: Different User Profiles and Protocols

1. Bitcoin holder
2. Bitcoin trader
3. Ethereum holder
4. Ethereum App user
5. Ethereum only since merge (or show all using a time-series on emissions)

5.3 Statistical Analysis

Statistical analysis of a random sample of addresses

will it be possible to get a sample of bitcoin xpub. Otherwise focus on ethereum analaysis before & post merge

5.3.1 Validation and Sensitivity Analysis Results

Validation Results

Sensitivity Analysis Findings

5.4 Limitations and Future Work

5.5 Further Opportunities for Blockchain and Sustainability

Chapter 6

Conclusion

Chapter 7

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