White Paper:
The Cardano Carbon Footprint

Cardano Layer 1 Carbon Emissions: A 2024 Study

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Executive summary

1. General Introduction
This section outlines the urgent need for robust carbon accounting in blockchain ecosystems amid climate change, spotlighting Cardano's Proof of Stake (PoS) protocol as a sustainable alternative to energy-intensive Proof of Work (PoW) systems like Bitcoin. It introduces the Greenhouse Gas (GHG) Protocol as the leading standard, categorising emissions into Scope 1 (direct), Scope 2 (electricity-related), and Scope 3 (other indirect). Challenges include inconsistent Scope 1 inclusion and Scope 3 complexity, with novel methods like E-liability and Markets in Crypto-Assets (MiCA) regulations proposed to enhance accuracy. The focus is on establishing a standardised, transparent methodology for calculating Cardano's carbon footprint to combat greenwashing and support climate goals.

2. Blockchain Scope and Boundaries
This section tackles two key shortcomings in blockchain carbon accounting: the exclusion of Scope 1 emissions and unclear operational boundaries. It argues for including Scope 1 emissions (e.g., operator heating or fuel use), significant in PoS systems like Cardano due to their low electricity use, aligning with the GHG Protocol's completeness principle. Boundaries are defined by focusing on Layer 1 (mainnet) as the essential, controllable core, excluding non-essential activities (e.g., marketing) and upstream/downstream emissions (Scope 3). A control-based approach assigns responsibility to Stake Pool Operators (SPOs), with annual boundary re-evaluation proposed to adapt to Cardano's evolution.

3. The Cardano Carbon Footprint - Accounting Methodology
The methodology quantifies Cardano's Layer 1 emissions, emphasising Scope 1 (e.g., SPO onsite combustion) and Scope 2 (node electricity use via the location-based method). It details parameters like SPO numbers, device energy consumption, and regional carbon factors, estimating combined Scope 1 and 2 emissions. Scope 3 is briefly addressed (e.g., hardware lifecycle), but remains outside this work's focus. Recommendations include renewable energy adoption and transparent reporting to minimise Cardano's footprint, supporting its sustainability ambitions.

Scope 1 Emissions, $_{2024}$	156.2 tCO_2e
Scope 2 Emissions, $_{2024}$	710.3 tCO_2
Combined Scope 1 and 2 Emissions, $_{2024}$	867.2 tCO_2
Including 20% Uplift, $_{2024}$	1052.3 tCO_2

ForeWord

Pond Foundation is a Swiss-based, international non-profit that supports organizations to determine their carbon footprint. We do this for pond Foundation member companies and as consultants for non-members. Our emissions calculations have been verified by Inteco, an ISO accredited auditor, as being completed in accordance with ISO standard ISO14064-1 Greenhouse gases: Quantification and reporting of greenhouse gas emissions and removals.

Pond Foundation has engaged with Christian Unger from SHIFT Pool to review this Carbon Footprinting White Paper for Cardano Layer 1. We consider it to be a high quality, foundational report that not only provides a first calculation of the Cardano blockchain's footprint, but that provides a strong basis for further discussions and considerations for future additions and amendments to the reporting logic.

Our experience with calculating carbon emissions according to ISO14064-1 is that it's critical to lay out all the assumptions and the scope, boundaries, and accounting methodology. This provides the basis for objective review and discussion. Defining the boundaries is a challenge with blockchain emissions calculations but the White Paper overcomes this challenge with great clarity and reasoning. It's less important that the reasoning is 100% correct than it is to be clear. This allows an informed discussion and debate as to what could or could not be included in the future. The White Paper does this.

The White Paper also describes clear logic on inclusions and exclusions, and again, provides a strong basis for the broader Cardano community to debate the points and to change the calculation approach in the future, should they decide to do so. Critical here is that the White Paper has established a foundational baseline and a path to ongoing development and refinement of the calculations.

The approach to calculate Scope 1 and 2 emissions is correct and in accordance with the ISO14064-1 standard. At this stage, it's too premature to include a full accounting of Scope 3 emissions, but again, the White Paper provides a good discussion and rationale for future inclusions and expansion, at least to include some of the easier to calculate Scope 3 emissions.

It is our view that the White Paper is an excellent piece of work. We acknowledge that we are conflicted in this statement by the fact that we are one of the partners to the Project Catalyst project that funded the Paper's development. That said, it's not in our interest to praise or discredit. It's important to us to maintain our credibility, and in this respect, we're happy to state unequivocally that we believe the report to be an excellent foundational calculation for Cardano Layer 1 carbon emissions.

Scott Poynton
Pond Foundation **Founder and Board President**

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About this document

Guidance facilitating research and development of a transparent GHG accounting methodology that captures a more complete picture of layer 1 carbon emissions of blockchains is needed to enable a clear path to a climate positive economy in this space.

This document focuses on the more recently developed Proof of Stake protocol used first by the Cardano blockchain. Its lower hardware electricity consumption means that other aspects of emission, less considered for Proof of Work blockchains, now become significant. It aims to discuss and define the boundaries of a decentralised community, to identify the responsible parties and help develop better accounting – perhaps identifying and monitoring carbon impacts on the ledger itself.

This document is the first part of a Catalyst funded project aiming to define the methodology for Cardano Carbon Accounting. This work has been initiated by a group of Stake Pool Operators, climate activists and scientists, working with a set of experts in the blockchain and carbon accounting space to review and improve its development. We seek an initial standard that allows us to define the path to a carbon neutral blockchain with transparency. It is important to ensure that all impacts are accounted for and acted upon.

This document does not:

- Go into detail on defining Scope 3 upstream and downstream emissions, instead focusing on defining essential Scope 1 & 2 emissions and their boundaries.

Objectives

This Cardano Carbon Footprint work is designed with the following objectives in mind:

- To provide meaningful information to **help fight climate change**
- To help all entities participating and utilising the blockchain to prepare **a true and fair account of their emissions**, through the use of a standardised and principled approach
- To **simplify and standardise** the compilation of a blockchain GHG inventory
- To ensure **a transparent approach**, to correctly account for the emissions generated by the blockchain and enable improvement over time
- To provide a means **to reduce Cardano carbon emissions** under the control of participants and thereby facilitating the sustainable low and potentially a no-emissions growth of Cardano

Abbreviations and Definitions

- Blockchains - decentralized, immutable, digital ledgers shared across a peer-to-peer network
- Carbon Emissions Factors - are conversion factors allow organisations and individuals to calculate GHG emissions from a range of activities, including energy use, water consumption, waste disposal and recycling, and transport activities. (page 13, ref [1])
- CIP - Cardano Improvement Proposal
- MiCA – Markets in Crypto-Assets Regulations; Regulation (EU) 2023/1114 of the European Parliament and of the Council of 31 May 2023 on markets in crypto-assets
- Node - a device running the software of a specific blockchain; Node types depend on the architecture and design needs of a specific blockchain protocol [2]
- PoS - Proof of Stake
- PoW - Proof of Work
- GHG - Greenhouse Gas

- GHGP - Greenhouse Gas Protocol
- Primary data - Information you collect yourself directly from the source, like through surveys, interviews, or observations
- Secondary data - Information someone else has already gathered and published, like in books, articles, or online reports
- Scope 1 - GHG Protocol terminology for direct emissions from activities
- Scope 2 - GHG Protocol terminology for indirect emissions from electricity use
- Scope 3 - GHG Protocol terminology for indirect emissions from upstream and downstream activities
- SPO - Stake Pool Operator
- Value Chain - refers to all of the upstream and downstream activities associated with the operations of the reporting company, including the use of sold products by consumers and the end-of-life treatment of sold products after consumer use. [3]
- WEEE - Waste Electrical and Electronic Equipment

1. General Introduction

1.1 Reason

Climate Change

Climate change is one of the biggest challenges of our time. Inaction and active delay strategies by existing fossil fuel dependent infrastructure has deferred meaningful change for too long.

The 2023 IPCC synthesis report on Climate Change [4] describes the current status of warming as “Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020.”. Importantly, the report states that despite this existing knowledge, “Greenhouse Gas Emissions (GHG) have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, and among individuals”.

The impacts are already obvious, with ‘many weather and climate extremes in every region across the world, impacting developed nations and even more so vulnerable communities who have historically contributed the least to the current climate change’ (adapted from [4]).

The first climate refugees from the island nation Tuvalu were officially recorded in 2014 [5] when the global average sea level was about 50mm higher than the 1993-2008 average and nearly 20 cm higher than it was at the start of the industrial revolution in 1880 [6].

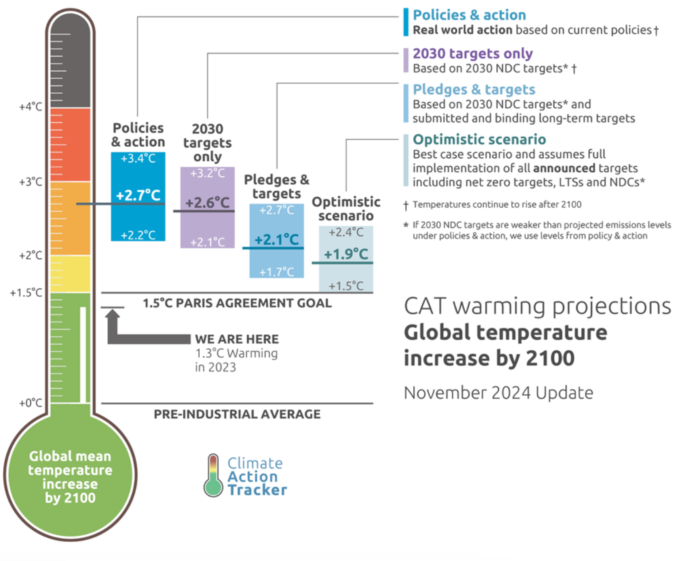

Figure 1: Climate Action Tracker [11]

In Bangladesh, it is predicted that 17% of the country will be submerged by 2050, and 20 million people will lose their homes [7]. Even in western nations such as the UK and the USA the rising sea level is already impacting people's lives [8], [9].

If temperatures rise higher than 1.5°C or even go 2°C above pre-industrial levels, negative consequences are already predicted to be extensive on biodiversity, water availability and water-related hazards, food production, extreme weather events and on our settlement key infrastructure [10]. However, we will struggle to stay as low as 2°C, with currently planned emissions-reduction policies and actions only setting us on track for ~2.7°C (Figure 1, [11]).

In order to stop the full impact of excessive global heating, we need to reduce global GHG emissions to zero ASAP and emissions capture technology is needed at scale to have any chance to keep the world to the 2°C target the United Nations set in the 2015 Paris Agreement. [12]

Blockchain impact & sustainability

Blockchain is much more than decentralised money, it is an immutable ledger. It has the potential to help us tackle climate change if sustainability is considered [13].

The heavy environmental impact from electricity consumption of the world's first blockchain, Bitcoin, has not been considered a significant issue from its outset. However, more recent smart blockchains such as Cardano or Ethereum have taken environmental sustainability into account, and can do so much more, while consuming less. Their immutable ledgers can help account for carbon emissions, track and monitor the progress of climate actions around the world and provide automated rewards for individuals, companies or governments for taking part in sustainable practices.

For example, the issue of "double counting" can be resolved using immutable blockchains as they allow us to store tree planting data transparently forever. So-called "double counting" occurs when two or more parties claim credit for the same emissions reductions, and can easily undermine the efficiency of carbon markets. [14]

Whilst blockchains can be part of the solution to the climate crisis facing the world, it is important to ensure that with its exponential growth this technology does not become part of the problem. Otherwise, its adoption will be questioned and rightly so [15]. This means the blockchain community needs to make every effort to keep energy consumption low and offset any remaining emissions while it grows. Arguably, it needs to be doing more environmental good than harm to earn its legitimate place in a world that is currently trying to keep from burning and drowning.

This is particularly important for the Cardano blockchain, which has a focus on becoming the people's blockchain in countries where there is no easy to access banking systems. A trusted technology platform should not bring additional damage to the local population, especially one vulnerable to climate change, or contribute to the global problem while actively onboarding millions of new users.

Proof of Stake (PoS) vs Proof of Work (PoW)

Proof of Stake (PoS) and Proof of Work (PoW) are two major consensus mechanisms (protocols) for blockchains to verify transactions and add them to the blockchain. For a blockchain to remain secure, it must have a mechanism to prevent malicious users from taking over the validation of these blocks. The newer PoS protocol has been found to be equally safe compared to PoW in peer-reviewed scientific literature [16].

In a PoS blockchain such as Cardano, blocks are added by 'minters' or 'validators', while in a PoW blockchain (e.g. Bitcoin), this task is carried out by 'miners'. The main difference in terms of environmental impact of each of these protocols is the much-reduced amount of computational work required for a PoS consensus algorithm compared to PoW. In a PoW blockchain, blockchain miners use similar amounts of electricity to countries like Ukraine or 0.64% of world electricity consumption in April 2023 [17]. In comparison, PoS protocols use many thousand times less electricity [18], [19].

Therefore, on top of their high functionality, PoS blockchains will be able to deliver their sustainability solutions from a much better starting position.

1.2 Current and Novel Carbon Accounting Standards

Carbon Accounting standards are important

There is a clear need for standards on carbon accounting so we can compare accounts, quality control them and know their strengths and weaknesses. More importantly, improvements can be made collectively. This is particularly important as throughout human history, the world has been within a limited temperature band determined by the Greenhouse gases (GHG) in our atmosphere (as described in the above section on climate change). It is clear that we currently add GHGs much faster than they are removed from the atmosphere resulting in dangerous global warming that is causing unprecedented change that could be prevented through the reduction and eventual zeroing out of GHG emissions.

However, to actually measure how much we as individuals, as well as companies, cities or indeed blockchains, are contributing, we need to account for them in a standardised way. Quality carbon accounting makes it possible to prioritise our actions, which is critical as the world is highly dependent on energy, and changing the generation and use of energy is a difficult and costly endeavour.

Equally important, a standardised approach allows for quality control, holds organisations and people to account for their actions and prevents dangerous greenwashing.

GHG Protocol standard

The leading approach to carbon accounting is the Greenhouse Gas (GHG) Protocol [20], which is a joint initiative of the World Resources Institute and the World Business Council for Sustainable Development.

The GHG protocol sets a standard for Companies and Organisations, Governments (Corporate Standard) for Cities, for projects and indeed continues to develop and update these standards. Most large companies (92% in 2016) are using the GHG protocol directly or indirectly to measure, manage and report their emissions [21].

The GHG Protocol classifies carbon emissions into three main categories: Scope 1, direct emissions; Scope 2, upstream indirect emissions associated with purchased electricity and heat; and Scope 3, all indirect upstream and downstream emissions.

Scope 2 and Scope 3 are both indirect emissions, but Scope 2 is separated out because it is relatively easy to measure, while Scope 3 emissions are mostly very complex to determine.

Challenges with the widely used GHG Protocol standard – Scope and data accuracy

Scope 1 direct emissions are the basis for valid accounting as they are the only corporate emissions that go into the atmosphere on site. However, it is a challenge to draw a line and define what to include in carbon accounting with regards to indirect emissions. Upstream and downstream emissions sources are often multiple times higher than Scope 1 emissions [22], but this very heavily depends on where measurement starts or ends.

While Scope 1 and perhaps Scope 2 emissions can be determined with some accuracy and are directly associated with an entity, Scope 3 upstream and downstream emissions are often not accounted for correctly. Due to their variety and amount, it is difficult to collect emissions data from all inputs/suppliers and downstream use. However, the GHG protocol expects companies to gather Scope 3 emissions data and while it expresses a preference for primary data, it does allow for secondary data. In practice, most companies are now reporting Scope 3 emission with secondary industry average data, thereby undermining the integrity of these measurements and making it difficult to reduce them. Governments and standard setting organisations recognise this complexity, hence requirements often only include the monitoring of aspects of Scope 3 emissions, whilst reducing them is mostly voluntary.

For the reasons outlined, initial carbon accounting strategies should require that Scope 3 emissions data should start to be gathered and grouped, but an initial focus on Scope 1 and 2 emissions is a sensible first step.
However, it is noted that new accounting methods to help determine an accurate Scope 3 footprint, such as the E-liability method, are currently in development [23].

E-liability method for supply chain emissions

The E-liability method (https://e-liability.institute/about-e-liability/) is a recently proposed upgrade to carbon accounting to enable simple and accurate cradle-to-gate emissions of any product or service. It provides a solution to address the challenges with Scope 3 emissions accounting mentioned above. It could enable the blockchain and its users a more accurate emissions accounting, adding up emissions of a product or service while it is going through the value chain. The accounting method itself would provide an additional utility for blockchains as the accounting of those emissions could be tracked through the blockchain itself.

New mandatory sustainability indicators in Markets in Crypto-Assets (MiCA) Regulation (2023)

MiCA Regulation: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1114

This new regulation will require the determination of the below indicators, which includes Scope 1 and 2 emissions as discussed in this manuscript.

10 sustainability indicators currently proposed for crypto assets, which will be required for trading of any crypto asset in the EU [24].

1. Energy consumption
2. Non-renewable energy consumption
3. Energy intensity per transaction
4. Scope 1 - controlled emissions
    - "Scope 1 GHG emissions, expressed in tonnes (t) carbon dioxide equivalent (CO_2e) per calendar year for the validation of transactions and the maintenance of the integrity of the distributed ledger of transactions"
5. Scope 2 - purchased electricity

    - "Scope 2 GHG emissions, expressed in tCO2e per calendar year for the validation of transactions and the maintenance of the integrity of the distributed ledger of transactions"
6. GHG intensity
7. Generation of Waste Electrical and Electronic Equipment (WEEE)
8. Non-recycled WEEE ratio
9. Generation of hazardous waste
10. Impact of the use of equipment on natural resources

1.3 Challenges and Guiding Principles of Blockchain Carbon Accounting

To tackle climate change, we must reduce our emissions and remove any left-over emissions from our atmosphere by investments into carbon offset projects.

To ensure we are reducing emissions and offsetting a sufficient amount, it is of high importance to get truly representative estimations of carbon usage. As the calculated values will always be near estimates, it is important to ensure all emissions are captured and that they tend to overestimate to ensure any actions are sufficient to zero out emissions.

One thing the Climate Neutral Cardano Alliance noticed, when initially estimating Cardano emissions for the 'Cardano Forest' project in 2021 [25], was that the focus of carbon emissions accounting on other blockchains is heavily biased towards electricity consumption of the validator nodes. Considering our knowledge about carbon emissions and accounting as summarised above, we noted initial accounting generally focussed solely on electricity consumption.
This was concerning as the various other types of emissions were not yet considered, and hence this methodology would lead to underestimating blockchain emissions. In particular, direct (Scope 1) emissions had been excluded in several accounting scenarios [26], [27], [28], [29]. On top of not accounting for Scope 1 emissions, Scope 2 electricity emissions are accounted for in many different ways and resulting in vastly different numbers (see Appendix C).

In any standard carbon accounting, emissions should be accounted for as direct and indirect emissions. The direct emissions of a company or organisation, are e.g. heating of work spaces generated through combustion of gas or oil on site. The direct emissions (scope 1) and our electricity consumption (scope 2) represent most of blockchain energy consumption and can be controlled by the blockchain community. Hence accounting for both Scope 1 and Scope 2 emissions is essential as it directly shows what we are responsible for and what we can practically reduce.

If every organisation or person accounts for their Scope 1 (and 2 emissions), collectively this will provide the upstream or downstream emissions (Scope 3) associated with each as detailed in the new E-liability approach to carbon accounting introduced above.

Challenges:

1. Scope 1 direct emissions are the basis for valid accounting as they are the only corporate emissions that go into the atmosphere on site. However, most often those direct Scope 1 emissions are excluded from blockchain accounting and instead all the focus is on indirect electricity consumption (Scope 2).

2. Furthermore, it is a challenge to draw a line and define what to include in blockchain carbon accounting with regards to direct and indirect emissions. Scope 2 emissions from electricity

consumption have shown a variety of results because they are calculated with a variety of inputs (Appendix C). These need to be standardised.

3. Scope 3 Upstream and downstream emissions are often multiple times higher than Scope 1 emissions [22], as they provide the platform for a whole new ecosystem. However, determining all upstream and downstream emissions is very complex, as millions of users and thousands of blockchain developers are constantly evolving and the utility of the blockchain increases over time.

‘Completeness’ and other principles of the GHG protocol

Completeness is one of five basic principles set out in the GHG protocol, alongside ‘Relevance’, ‘Consistency’, Transparency and ‘Accuracy’. In the GHG protocol completeness means “All relevant emissions sources within the chosen inventory boundary need to be accounted for so that a comprehensive and meaningful inventory is compiled.“ The protocol also states that any specific exclusions must be disclosed and justified. Excluding direct emissions, as has been done by many of the above mentioned blockchain accounting reports, is contrary to the GHG protocol and clearly not helpful to provide an accurate measure of emissions. The inclusion of these perhaps less-material emissions (in PoW protocols), is becoming very significant for PoS protocols, due to their much lower server electricity consumption.

Value Chain Carbon Accounting

A lot of interest in Carbon accounting lies in the assigning of Scope 3 emissions of the blockchain so other organisations that use blockchain as a tool can include these emissions in their Environment Social and Governance (ESG) reports.
How to assign blockchain emissions has been described elsewhere using holding-based, transaction-based and hybrid methods [30]. The wider impact of Cardano, including its total upstream and downstream emissions, will be outside the scope of this report. However, this will be discussed in the section on Scope 3 emissions.

Responsibility - Who is responsible for managing and reducing blockchain emissions?

As per the GHG Protocol, there are two distinct approaches to consolidate GHG emissions for corporate reporting, based on the structure of an organisation [31]: the equity-based and control-based approaches. The equity-based approach reflects economic interests or rights an organisation has to the risks and rewards of an operation, whereas the control-based approach accounts for the GHG emissions from operations over which it has control.

As Cardano represents a decentralised community, its economic interests, risks and rewards will be difficult to define. In our opinion, this makes the equity-based approach difficult to implement. Instead, the control-based approach, which is further divided into operational and financial control criteria, seems more applicable to the Cardano ecosystem.

A blockchain is a distributed ledger with growing lists of records (blocks) that are securely linked together via cryptographic hashes. So, who is in control and what do they control? While the Cardano community has a degree of financial control via the newly developing governance structures, the easier things to define are the operational parts the Cardano community have control over. In particular the essential parts of the Cardano blockchain that provide the ledger functionality and are called mainnet or layer 1.

Power brings responsibility

The people and organisations controlling the aspects of that layer 1 infrastructure are responsible for managing and reducing layer 1 emissions. Once the emissions of the layer 1 infrastructure are defined, tracked and reported, the Cardano community with its Stake Pool Operators, delegators, lead organisations, and users, together have the opportunity and responsibility to reduce them. The next section focuses on defining those layer 1 boundaries and scope of Cardano carbon accounting.

2. Blockchain Scope and boundaries

Addressing two current blockchain carbon accounting challenges

This part of the report seeks to specifically address two shortcomings associated with currently available blockchain carbon accounting strategies:

(1) The lack of considerations of Scope 1 direct emissions and
(2) A definition of boundaries that describe the core of the (Cardano) blockchain.

Addressing both shortcomings is essential to improve carbon accounting and to be able to control and potentially reduce the emissions the blockchain operators have control over.

This report will not seek to address the challenge of Scope 3 indirect emissions upstream and downstream other than defining the border on where they should start or end.

2.1 Challenge 1: A lack of Scope 1 emissions accounting when looking at blockchains - Suggest direct blockchain emissions (Scope 1) are to be included

As indicated in the challenges-introduction above, so far the carbon footprint estimates of blockchains only consider electricity consumption of its server and mining infrastructure. This leaves out actual direct emissions caused by its operators.

That means the actual principle of 'completeness' of the GHG protocol is not applied and could mean we significantly underreport blockchain emissions.

For example, the Cambridge Bitcoin emissions accounting method is purely based on its electricity consumption [29]. This may even be ok for Bitcoin as it is obvious that the largest part of its emissions are likely due to its Scope 2 mining related electricity consumption, thereby rendering building or employee related Scope 1 emissions as a much lower percentage of the total.

However, the approach of omitting those direct emissions is much more distorting when looking at Proof of Stake (PoS) blockchains whose electricity consumption is often several thousand-fold lower than Proof of Work (PoW) blockchains. Still, in carbon accounting done for Ethereum, Algorand and Solana purely Scope 2 electricity consumption has been considered [26], [27], [30] with Scope 1 emissions left out.

The GHG protocol standard 'completeness' criteria requires that 95% of all emissions need to be accounted for, so we will later show that Scope 1 emissions can easily exceed this in the case of Cardano and potentially other PoW blockchains that generally utilise low amounts of electricity. More importantly, these are emissions that are directly under the control of the Cardano community and especially the SPOs. So, alongside choosing the right cloud and/or electricity provider it is at the direct emission level where SPOs can make their stand to show how sustainable they are!

<u>Simplified example showing how Scope 1 can easily exceed 5% of Scope 2 emissions</u>

As a quick example for the significance of Scope 1 emissions let's look at a simplified Cardano stake pool running the minimum of two nodes on a bare metal server (one block producer and one relay). Assuming a node would use 25.5W [32], 2 nodes would use 36.7kWh in 30 days. At a 2023 UK grid carbon emissions factor of 0.20496 kg CO2e per kWh (Source: gov.uk/) this would mean 7.5 kg CO2e would have been emitted from electricity consumption during those 30 days. Assuming a Stake Pool operator in the UK spent approximately 6 hours on pool maintenance during this month, their emissions based on the average emissions of a UK citizen being 4.7 tonnes CO2 per year (2022 data from https://ourworldindata.org/co2-emissions) would be about 3.2 kg CO2 for their work input. This would be 42% of the emissions from server electricity use and could reach the amount emitted from server electricity use itself if maintenance requirements increase. This could be accounting for gas heating at home or in the office, driving to their office or other emissions that are still prevalent in the UK and any company would have to report emissions on. It is evident that just spending this time on Cardano maintenance could easily increase emissions by more than the 5% specified as inclusion criteria by the GHG Protocol.

Equally importantly, and referring to the control element, these emissions are something the stake pool operator can impact by switching to a heat pump and renewable energy or using an electric car. Furthermore, any additional maintenance required would increase those emissions as SPOs have to spend more time. Hence, detecting this significant impact will provide an incentive for node developers and the Cardano community itself to consider maintenance related workload as an important aspect of the carbon burden of the ecosystem.

Besides the obvious impact of direct emissions, as previously outlined, accounting for Scope 1 emissions is key to any carbon accounting and any carbon accounting standard and there is really no good reason not to include these emissions as there are well established methods to determine them.

A questionnaire to SPOs can initially determine approximate time requirements and direct emissions associated with that time. Based on location of stake pools and average estimates for node upgrades and key changes such emissions can be estimated and such data may be automatically collected in the future. More on that can be found in the third part of this paper.

In conclusion, Scope 1 emissions need to be included in blockchain emissions.

However, to further answer the question of emissions it is important to define the blockchain boundaries.

2.2 Challenge 2: Definition of boundaries - Who and what is part of the blockchain and should be accounted for?

Which emissions should be associated with a blockchain? Where does upstream and downstream start when accounting for Scope 3 emissions?

The blockchain value chain is extensive and very much relies on existing infrastructure. Therefore, it is important to define which emissions we, as the blockchain community, are responsible for and can actually impact and reduce. As already outlined in the above section on responsibility, if you can control a thing operationally or financially you have a responsibility to take action.

Before we can start talking about responsibility, we need to define what the blockchain is and who is running it. Note, although we are referring to general principles for blockchains, we will be basing the examples on our understanding of Cardano and there may be some areas that do not apply to other blockchains now or in the future.

To emphasise the point on scope and the importance of boundaries please ask yourself whether or not you would include the responsibility of reducing the following carbon emissions to the blockchain operator?

Where would you count the following:

- the electricity used by servers or office spaces needed to run stake pools?
- the energy consumption of hardware required for the internet connection to your servers?
- the energy consumption of the computer hardware of the blockchain end user running interfaces to the blockchain, i.e. wallets?
- the energy consumption of hardware for applications that utilise the blockchain but do not maintain the ledger?
- the energy required for disposal of electronic waste?
- the energy required for the production of the hardware required to run the blockchain?

Some of the above examples may be straightforward to define as directly related to a blockchain and others much less so. Hence, this part of the paper attempts to describe a framework that helps define the boundaries regarding GHG emissions.

To help us think about what to include we looked at the commonly used definition of blockchain layers to delineate blockchain.

Blockchain layers

There are various ways of breaking down blockchains and one standardised way would be the Open Systems Interconnection (OSI) model [33]. The OSI breaks things down into 7 layers (physical, data link, network, transport, session, presentation, user interface), but we found it very difficult to use in the context of defining who is running the blockchain and assigning responsibility for emissions as several layers are actually handled by the same operators, software and hardware.

A more practical 4-layer-model describing the technology stack is commonly used to describe the blockchain ecosystem and breaks things down into 4 layers with layer 1 being the foundation layer (Mainnet, main chain, base layer) as described by most major blockchains (see Table 1). More importantly this layer 1 usually defines the essential blockchain functionality, which is helpful if we want to define the boundaries of a blockchain. For example,Ethereum, Cardano or Bitcoin all clearly define layer 1 and 2 functionality [34], [35], [36].

It is noted that while layer 1 and 2 are well defined, layers 0 and 3 are more open to interpretation [37], although the example layer definitions as shown in Table 1 below seem to be commonly used and set the boundaries well.

Following the layer descriptions in Table 1, we focus on the general layer 1 definition to set boundaries for controlled Scope 1 and 2 blockchain carbon accounting. The layers above and below lend themselves to be accounted for in the upstream and downstream category generally described as Scope 3 emissions associated with that blockchain. More about that in the Scope section below.

Table 1. Cardano Blockchain Layer 0-3 definitions

	Source: Coinstats (Ref [38]) (adapted)	Source: Essential Cardano [35]
Layer 0	**M**ade up of components that help to bring the blockchain to life. This is the technology that allows blockchain networks to function. The internet, hardware, and connections that allow Layer 1 to work effectively are examples of Layer 0 components.	n/a
Layer 1 (Foundation Layer, Main Net)	The security of the foundation layer is based on its immutability. When people discuss Ethereum or Cardano, they are referring to the main network, also known as layer one. This layer is responsible for consensus methods, programming languages, block time, dispute resolution, and the rules and parameters that assure a blockchain network's core functionality.	Layer 1 is the base network upon which rest layer 2 solutions. Cardano is the layer 1 (the base network), which itself includes three independent layers: ● Network layer ● Consensus layer ● Ledger layer
Layer 2 (Scalability Solutions)	**Layer 2** is an overlapping network above Layer 1. It is used by protocols to promote scalability by separating some interactions from the base layer. As a result, smart contracts on the main blockchain protocol only handle deposits and withdrawals, while ensuring that off-chain transactions adhere to rules. An example of a layer two blockchain is Cardano's Hydra protocol or Bitcoin's Lightning Network.	Broadly speaking, layer 2 solutions address the scalability issue inherent to layer 1 chains. Built on top of an existing blockchain (just as adding a new tier to a wedding cake), layer 2 protocols perform a great deal of processing work that would otherwise happen on the main chain. This increases the main chain's throughput. An added bonus is that, while the layer 2 solution does the hard work, the layer 1 retains its security.
Layer 3 (Application layer)	The Layer 3 projects serve as a user interface while concealing the technical details of the communication channel. As mentioned in the blockchain architecture's layered structure,Layer 3 apps are what give blockchains their real-world applicability. An example for a layer 3 application are the Daedalus or Eternl wallets.	n/a

Defining only layer 1 (main chain) as in scope for blockchain carbon accounting based on 'essentiality' and 'control'

Using the two criteria of operational control and essentiality to define the blockchain boundaries.

Anything related to a blockchain that is not essential to run the main chain and can not be directly controlled by the blockchain operators is considered to be outside the boundary. These activities/infrastructures will only be included in indirect Scope 3 emissions upstream or downstream of the blockchain.

Operational control is a key criterion used in the GHG protocol standard to help us define the inventory boundary. Furthermore, we seek to identify essential core components that provide a fully functional blockchain that can stand alone, but allows us to easily separate non-essential parts.

- **'Essentiality'** means that only the parts required to run and maintain the core functions are to be included.
  - Every part that is run and maintained independently of the core functions and builds on top of the layer 1 should be excluded from the core operational boundaries.
- **'Control'** means whether or not an aspect is changeable through the node software and the blockchain community can influence the code (to reduce impact).

Another criterion to help determine whether or not to include certain elements as within the Scope 1 and 2 emissions and carbon accounting boundaries is to ask yourself if this energy consuming element is already directly controlled and accounted for through other entities. If not, it should be considered to be included in the blockchain accounting in order to ensure its emissions are indeed reduced over time.

How do these two criteria apply to the blockchain layers?

Table 2. Applying 'essentiality' and 'control' criteria to the individual blockchain layers.

Layers *as defined in Table 1	Essential for core blockchain functionality	Controlled by blockchain operator and community directly
Layer 0	yes	no
Layer 1	yes	yes
Layer 2	no (maybe later)	maybe
Layer 3	no	no

Layer 0 defines the energy and internet infrastructure and are indeed required to operate the blockchain. However, whilst this basic infrastructure is essential for the blockchain functionality (i.e. the internet connection), it is not directly controlled by the blockchain operators and can only be influenced indirectly.

Layer 1 is defined as the base or foundation layer and makes it the obvious candidate as the boundary for blockchain carbon accounting. It provides the essential functionality (as outlined in the next section) and is controlled by the blockchain operators. It clearly delineates from other blockchain layers, such as layer 0 infrastructure and other scalability functions provided by layer 2 scalability solutions or the layer 3 application layer. These additional layers are built on top of the layer 1 blockchain, but they are not essential for its operation.

Layer 2 is the most unclear layer with regards to being accounted for by one blockchain. This is partially because they are still in development and hence they do not yet provide essential functionality. However, they may be essential in providing future functionality that the blockchain can not be without e.g. Hydra, which currently is not essential for Cardano, but may be in the future. Hence, new energy consumption providing essential functionality should be reviewed regularly and clearly defined as included or excluded in carbon accounting. At this stage, the Cardano blockchain provides a full set of core functionality without such scalability solutions, hence it is suggested to account energy consumption of any layer 2 hardware separately. Some of the scalability provided by layer 2 solutions will add functionality to the layer 3 application layer and it may be best to account for those with layer 3.

Layer 3, or the application layer, is easily delineated from the blockchain and hence downstream of the main functionality. Applications are not essential for the basic operation of the blockchain, but instead build onto the blockchain. These applications could utilise one or more blockchains to provide functionality and are in themselves separate businesses that could run independent from any one blockchain. Hence, from a carbon accounting point of view, they are not essential and are only indirectly linked to one specific blockchain community. This also means they would be able to report their own carbon emissions depending on the energy use for their own business. If reported, these could be included into downstream Scope 3 emissions of a blockchain.

Conclusions

Using the above test, we propose only layer 1 emissions are the emissions of the core blockchain and other layers fall outside (upstream or downstream) of the blockchain carbon accounting.

To ensure clarity when reporting blockchain carbon emissions until standards are defined, additional information should clearly indicate what has been included and excluded in carbon accounting.

So, if layer 1 is the blockchain boundary, let's define layer 1.

Note: The Cardano node software is the top-level repository that enables the layer 1 functionality [39].

Cardano Layer 1 definition and functionality

Layer 1 functionality – Cardano node - Network layer, Consensus layer, Ledger layer

Source [35]:

"... Cardano is the layer 1 (the base network), which itself includes three independent layers:

- Network layer
- Consensus layer
- Ledger layer

As a whole, these three layers form the layer 1 solution that is Cardano."

This layer separation (detailed in Table 3) allows Cardano to optimize each component independently—e.g., upgrading the network protocol without altering consensus or ledger rules—and supports its focus on formal methods and scalability.

Table 3. The three sub-layers of layer 1 in the Cardano blockchain.

Network layer	• maintains the connections between all the distributed nodes in the Cardano network • obtains new blocks from the network as they are produced by block producing nodes • builds newly minted transactions into blocks • transmits blocks between nodes. Acts as the communication backbone, ensuring that data (transactions and blocks) flows efficiently and reliably across the decentralized network. It's the infrastructure that keeps nodes synchronized.
Consensus layer	• runs the Ouroboros consensus protocol.: takes decisions like adopting blocks, choosing between competing chains (if there are any), and deciding when to produce blocks of its own; and • divides time into epochs and slots (short time intervals), selecting a "slot leader" from the pool of stake holders to create and validate new blocks. Provides the decision-making framework that ensures agreement on a single, secure blockchain. As discussed earlier, its core duties—leader election and chain selection—drive Cardano's proof-of-stake system.
Ledger layer	• specifies what the state of the ledger looks like • specifies how the ledger must be updated for each new block. Manages the accounting and state transitions, ensuring that every change to the blockchain's state (e.g., token transfers, smart contract executions) is consistent, verifiable, and formally specified. The ledger layer consists exclusively of pure functions that specify the transitions between successive ledger states, as derived from the formal ledger rules, using the Extended UTxO (EUTxO) accounting model. The state transitions are driven by the set of transactions that are contained within the Cardano blocks, and by major events such as epoch boundary transitions.

Cardano blockchain operations - elements of the layer 1 blockchain consume energy and hence emit Greenhouse Gases

The information in Table 2 and 3 does not yet tell us who or what provides this functionality for the blockchain, only that this functionality is essential for the blockchain. The Cardano blockchain provides this functionality by running Cardano software on thousands of nodes around the world.

The nodes that maintain the blockchain 24/7 are run by **Stake Pool Operators** (SPOs), who are rewarded by the blockchain protocol for the blocks they produce.

Energy consumption of layer 1 functionality is therefore directly dependent on the node software and the number and type of computers utilised by the network of SPOs.

Subsequently, the emissions from electricity consumption depend on the amount and type of energy utilised i.e. standard or renewable grid electricity or self-generated electricity from fossil-fuelled or renewable powered generators.

Other than the electricity used for operating the computers, the Stake Pool operator’s physical actions while maintaining the node can also have associated direct and indirect emissions and those depend on how much time the SPO spends, how the office is heated or cooled and whether or not the SPO has to travel to the place of work.

The cardano blockchain code also impacts its energy requirements

The **node software** itself is provided by the Input Output (https://iohk.io/about/) developer team and controlled through Cardano Governance mechanisms e.g. Cardano Improvement Proposals (CIPs), which the Cardano community can vote on.

This is important, because energy consumption is impacted by node functionality and associated server requirements to run the code.

Standardised energy and carbon accounting protocols will provide helpful feedback on how code changes impact the network’s energy consumption and allow the community to monitor and manage this impact through votes and asking for more energy efficient coding.

Table 4. Breakdown of layer 1 blockchain emissions as defined in Scope 1, 2, 3 GHG protocol scopes

GHG Protocol Scope	Definition	Carbon accounting required
Scope 1	Direct emissions generated by **operation and maintenance of the layer 1 blockchain and its layer 1 operators**. I.e. running on-site work spaces and/or servers: any direct combustion from gas heating or generators or cars as utilised by node operators	**Yes**

Scope 2	Indirect emissions from purchased electricity, cooling or heating for the **operation and maintenance of the layer 1 infrastructure and its operators**. I.e. Stake Pool electricity consumption from the grid	**Yes**
Scope 3	Indirect emissions generated as a consequence of the activities of the blockchain, but not controlled by the layer 1 blockchain operators. I.e. end user electricity consumption for computers or mobile phones	For information only

Proposal for annual re-evaluation on blockchain operational boundaries

For smart blockchains like Cardano, who are constantly evolving by implementing scaling and voting solutions, a re-evaluation of essential components should take place to assess whether new layer 2 solutions (like Hydra [40]) should be included as an essential part of its operational boundary. They should be included if these new layer 2 functions are widely used, and provide essential new functionality and/or they require significant infrastructure whose impact is not accounted for in other ways.

What energy consumption is to be included in layer 1 operation?

Based on the above arguments and in line with requirements for general GHG reporting, Scope 1 and Scope 2 emissions of the layer 1 blockchain are the core ‘Cardano emissions’.

Core Proposals:

1. Emissions must cover energy consumption by essential hardware to run all stake pool nodes for layer 1
2. Emissions must cover impacts from essential human efforts to operate and maintain the layer 1 infrastructure
3. Included emissions must be directly controllable by the operators of the blockchain, i.e. through influence of hardware use, choice of energy source or self-generation and maintenance efforts

Reasoning for these scope parameters: Measuring the scope 1 & 2 emissions of the above enables tracking of the efficiency of deploying and operating node software, including its operational and maintenance requirements.

The above suggested core emissions provide a defined set of emissions that can be directly associated with Cardano. However, to ensure emissions are defined clearly for standard setting, we must also decide on grey areas and suggest if they are indeed associated directly to Cardano or not.

Hence, we must propose what is not directly a Cardano footprint and suggest:

4. Exclusion proposals for scope 1 & 2 emissions as detailed below
5. All emissions outside of the layer 1 criteria, including the exclusion proposals, are to be accounted for as indirect Scope 3 emissions upstream or downstream of the core emissions

2.3 In or Out? - Should these items be included or excluded in Cardano Core scope 1 & 2 emissions reporting?

Please note that in our opinion there is no clear-cut answer to which items should be included and omitted, but the blockchain community alongside climate accounting experts should discuss and define a consensus on the matter that helps define the carbon footprinting of any blockchain.

Defining the scope will help to enable accurate accounting, which is currently leaving large swathes of blockchain impacts unassigned.

In general, it is proposed to exclude anything from the core Cardano emissions that is not obviously essential to the blockchain operation today, everything that is essential and under the control of the Cardano community must be accounted for. Aspects that are related but not essential to Cardano operations can be classed as upstream or downstream (Scope 3) emissions and could be defined and later grouped in multiple categories such as has been done in the GHG Protocol for corporate Scope 3 emissions.

The below proposals for exclusion detail a few activities associated with the Cardano blockchain that may or may not be included into the Cardano core emissions. The author suggests initially excluding them, based on the arguments made below. However, this should be discussed with other carbon accounting experts and the Cardano community to come to a consensus decision on exclusion/omission which could be altered over time. Details regarding what is included and omitted must be published alongside the carbon accounting for transparency.

1. Exclude? - SPO emissions not essential to operating and maintaining nodes i.e. time spend on marketing and engagement

Proposal 1: The associated emissions for time and efforts spent on collaborating and marketing of stake pools is arguably not essential to the operation of the layer 1 blockchain. Hence, it is proposed to exclude from core emissions (arguments below). Instead, it is suggested that only time spent on operating and maintaining the server hardware and node software should be accounted for.

This proposal has a very significant impact on the outcome of the accounting, because SPOs often spend significantly more time on marketing their pools than maintaining them.

Arguments for and against this exclusion require further discussion within the blockchain community and input from GHG accounting experts. However, we offer some initial thoughts here:

- arguments for exclusion of marketing and project work related emissions:
    - marketing and wider collaboration of Stake Pool operation is arguably unnecessary for running the layer 1 blockchain
    - simplifies the accounting, as the wide variety of partnerships and marketing conducted by blockchain operators can be difficult to assign to only one blockchain as much work is going into interoperability and projects that are not purely associated to the Cardano blockchain
    - exclusion of marketing would make it directly possible to visualise node version efficiency i.e. to evaluate impacts of software updates after CIPs and could enable a path to significant energy savings (due to the current efficiency of Cardano, including marketing efforts of the community could significantly outstrip core running emission and hence make it difficult to determine node efficiency)
    - these emissions are indirect and will be included into Scope 3 emissions

- arguments for inclusion of marketing and project work related emissions:
    - these marketing efforts would normally be included in emissions accounting from companies as per requirements in the GHG protocol
    - marketing is necessary to ensure stake and income to pools
    - much of the time spend by Stake Pool operators is on communication and marketing and not accounting these in Scope 1 & 2, would reduce focus on reduce emissions from it
    - these emissions would still have to be monitored as indirect emissions in Scope 3, but this would take focus away from them and make it harder to commit SPOs to reduce these emissions
    - inclusion could lead to SPOs to outsource marketing and artificially show lower emissions

2. Exclude? - Emissions of core companies associated to Cardano i.e. Input Output and the Cardano Foundation

Proposal 2: While both organisations 'Input Output' and 'The Cardano Foundation' provide key components for the development and growth of Cardano, they are not essential to operate the blockchain version today. Furthermore, company emissions accounting has a well defined carbon accounting standard and hence they should follow these accounting standards and control their emissions independently.

- arguments for exclusion of emissions from these companies from Cardano core emissions:
    - these companies are not required to maintain the Cardano blockchain directly, other companies can take their role
    - as independent companies they should do their own carbon accounting following corporate standards
    - they provide services for multiple blockchains (in the case of Input Output)
    - exclusion reduces complexity
    - if marketing related emissions are excluded from SPO emissions, then marketing and communications by these companies are also to be excluded

- arguments for inclusion of emissions from these companies from Cardano core emissions:
    - even though they are not absolutely essential to operate the blockchain, they provide essential components and updates that keep the blockchain safe and current
    - they employ hundreds of people and hence have a significant carbon footprint that is relevant to Cardano and can be controlled to some degree by the Cardano Community
    - While not essential, the Cardano Foundation is 100% focussed on expanding the Cardano ecosystem and hence adds to its footprint

3. Exclude? - Emissions of core Apps - like Cardano wallets and wallet apps

Proposal 3: While Cardano wallets are essential to connect and utilise the Cardano blockchain, they are apps built on top of layer 1. While at least one is needed per user, most users are utilising multiple apps depending on the applications they are interacting with and many wallets hold tokens from other blockchains or even supply services not essential to the layer 1 functionality.

While the operation of wallets will consume energy and cause emissions, these are built and operated by individual companies and hence we suggest that carbon accounting relating to wallets should be done in line with Corporate carbon accounting as defined in the GHG protocol.

- arguments for exclusion of emissions from blockchain wallets from Cardano core emissions:
    - wallets can hold non Cardano tokens and hence it becomes difficult to assign them only to Cardano
    - there are full node wallets like Daedalus with the energy mainly used by the wallet user and online wallets where much of the electricity is from the operation of software on company servers - monitoring and accounting will add significant complexity
    - it would be difficult to know how many wallet apps are used
    - the Cardano community itself has very little control over these apps, other than the impact as a consumer

- arguments for inclusion of emissions from blockchain wallets into Cardano core emissions
    - energy consumption from these wallets could be very significant
    - wallets are an essential part of the Cardano ecosystem

Further proposals currently excluded - i.e. Emissions from Testnet, Governance and Catalyst organisations

The Cardano ecosystem is complex and growing. Besides the above suggested exclusion, there are more participants or parts of the blockchain community that should be considered regarding inclusion or exclusion in the layer 1 emissions, but are not currently included into the emissions accounting.

For example, Cardano is operating a Testnet that will consume energy and it has unique governance and funding mechanism, i.e. Catalyst, which are inbuilt into the Cardano blockchain.

Testnets *- Scope 1&2 or not?*
Most or likely all blockchains, including Cardano, run one or more Testnets to test node software updates and new functionality before bringing them to the mainnet. These are run on separate nodes and use energy, but are not directly required for layer 1 functionality.

Governance functionality & Catalyst *funding - Scope 1&2 or not?*
Governance functionality is evolving strongly since the implementation of Voltaire, to develop a democratic body to direct the network. New governance support organisations, such as Intersect, while not yet essential, may need to be accounted for if they are essentially controlled and funded by the community. Also, Catalyst is an evolving platform which uses resources and energy. It is not currently essential for the blockchain to function, but is obviously integral to Cardano. The community could also influence how this is run and hence its energy consumption could be considered.

2.4 Iterations of Cardano Carbon Footprint

This work aims to develop a transparent iteration of the Cardano Carbon Footprint addressing some of the challenges described above and enabling further improvement over time. It addresses the two significant shortcomings identified in the beginning of this chapter 2.

The exclusion proposals above indicate the complexity of standardising blockchain carbon emissions beyond those challenges, but we suggest that addressing the initial shortcomings is a first step and already goes far beyond what anyone else is exploring.

There is additional functionality Cardano is using that is less easy to clearly assign as 'essential' parts of the blockchain, but which a standard should give some guidance on and accounting should clearly define as excluded or included.

- Stake Pool marketing and project development to increase stake
- Testnets
- Governance functionality (i.e. Catalyst, Intersect)
- Key companies to be included as essential (i.e.IOG - the Cardano founder company that develops the node software, Cardano Foundation)

Helpful tools and guidance to decide if emissions sources should be included

To assist in determining whether specific emission sources should be included in carbon accounting, the criteria outlined in Table 5 provide a standardised framework for decision-making. This qualitative approach assigns scores to various factors, offering a practical guide to evaluate the relevance of each source.

More detailed description:
Example Analysis: Should Stake Pool Marketing Be Included in Carbon Accounting (Scope 1 & 2)?
For Stake Pool Operators (SPOs), marketing efforts play a role in attracting delegators and building community support. However, marketing and project-related activities are not essential to maintaining a Stake Pool's operational uptime. The time and energy invested in these activities vary widely among operators. For some, marketing could constitute a full-time commitment (e.g., 40 hours per week) to grow their community and generate sufficient income, while others may invest minimal effort. Including these emissions in carbon accounting might seem logical to reflect average activity levels, but it's unclear whether this would meaningfully inform carbon footprint reduction strategies.

To assess whether emissions from Stake Pool marketing should be included, we can apply the qualitative criteria from Table 5, scoring each factor from 1 (Low) to 3 (High):

Access to Quality of data: 2
Level of influence: 2
Frequency of emissions generation: 2
Sector specific guidance: 1
Risk / Opportunity: 2
Outsourcing: 1
Cumulative Score: 10

Interpretation and Guidance
The cumulative score of 10 is borderline, based on the Pond Foundation's qualitative criteria (Table 5), which suggest that emission sources scoring above 10 should be included in carbon accounting. This threshold reflects a practical rule of thumb rather than an absolute measure, given the subjective nature of qualitative scoring. In this case, the result indicates uncertainty: marketing emissions could be excluded due to their non-essential role in Stake Pool operations and lack of sector-specific emphasis, yet their frequency and potential influence might argue for inclusion, particularly if blockchain networks aim for comprehensive transparency.

Qualitative Emission source Inclusion/Exclusion criteria list:

Table 5: Qualitative Emission Source Inclusion/Exclusion Criteria
Source: Adapted from Pond Foundation (2022), Greenhouse Gas Accounting Report, Annex II [41]. This table ranks criteria to justify the inclusion or exclusion of emission sources, assigning values from 1 (Low) to 3 (High) across six factors. A score exceeding 10 typically warrants inclusion.

Criteria	Assigned Value	Description
Access to & Quality of data	3	High: It is possible to collect information from communications with stakeholders directly related to the organisation. Primary data is available.
	2	Medium: although there is no direct communication with the parties in charge of the information, it is possible to identify basic information from the source. Secondary data is available.
	1	Low: the party in charge of the information is unknown.
Level of influence	3	High: it is possible to directly influence the generation of emissions from the source.
	2	Medium: the party in charge can be influenced to ensure the reduction of emissions from the source.
	1	Low: there is no reasonable possibility of influencing the emissions of the source.
Frequency of emission generation	3	High: the emission is generated on a daily basis
	2	Medium: the emission is generated more than once per month but less than once per day.
	1	Low: the emission is generated less than once per month.

Sector-specific guidance	3	High: There is secondary data or reliable reference sources that indicate that the source could have high significance within the inventory.
	2	Medium: The baseline data used do not conclude that the expected emission is high.
	1	Low: according to the information used, the consideration of this emission source is not described.
Risk / Opportunity	3	High: Increased emissions from the source expose the organisation to reputational, operational, or other risk.
	2	Medium: The analysis determines opportunities but not necessarily major risks.
	1	Low: No significant risks or opportunities associated with the emission source are identified.
Outsourcing	3	High: the process is contracted externally and constitutes essential business activities.
	2	Medium: it is contracted externally but does not constitute an essential business activity.
	1	Low: is not contracted externally by the organisation.

2.5 Proposed emissions accounting overview - summary table with examples

Table 6. Proposed emissions sources to be included in carbon accounting of the Cardano blockchain. *Note: The above discussed exclusion proposals have not been included in the table.*

Emissions source (Description)	Reported under GHGP Scope 1 or 2	Blockchain layer	Examples
Scope 1 - direct emissions			
Emissions from on site space heating required for operator/SPO activities during pool maintenance	Scope 1	1	office heating from direct combustion of fossil fuels (gas or oil, etc)
Emissions from travel required for operator/SPO for node maintenance	Scope 1	1	travel to office (fossil fuel combustion)
Emissions from space cooling required for operator/SPO maintenance activities	Scope 1	1	fugitive emissions from air conditioning used to cool home, office or servers
Scope 2 - indirect emissions from electricity			
SPO Emissions from electricity used to run barebone servers	Scope 2	1	electricity use from barebone servers run by Operator directly (i.e. operators pay for electricity or generate themselves)
SPO Emissions from electricity use of cloud servers	Scope 2	1	electricity use from cloud servers not operated by SPO
Scope 3 - upstream and downstream emissions - below only illustrative examples			
Emissions from from internet provision to connect Cardano nodes	Scope 3	0	emissions from internet provider to provide connection
Emissions from electricity use for routers and modems used to connect nodes	Scope 3	0	emissions from electricity use from home routers or Wifi
Emissions from Layer 2	Scope 3 -	2	emissions from

solutions like Hydra	downstream		operation of running Hydra servers
Emissions from Layer 3 solutions like Dapps	Scope 3 - downstream	3	emissions associated with running Cardano Apps like Decentralised exchanges, wallets, infrastructure
Life cycle emissions of SPO hardware	Scope 3 - downstream	3	emissions associated with production, transport and disposal of server hardware

3. The Cardano Carbon Footprint – Accounting Methodology

At its core, the Cardano Carbon Footprint methodology calculates the energy used by workstations running the Cardano Node software, which are managed by thousands of Stake Pool operators to maintain the blockchain. This energy figure for a single node is then multiplied by the total number of nodes operated by Stake Pools across the network to estimate the overall energy consumption.

Importantly, this includes not just the power drawn by the workstations running 24/7, but also the essential energy consumed by the operator's working setup—such as lighting, heating, or the interface required to access the nodes—needed to maintain the software and its associated hardware.

Finally, this combined energy use is converted into a carbon footprint by applying location-specific carbon factors, which reflect the environmental impact of these activities based on where they occur.

3.1 The scope and goals of the methodology

- Focus on Layer 1 Emissions: The methodology targets carbon emissions from the Cardano Layer 1 blockchain (the core operational layer), deliberately excluding emissions from Layer 2 (e.g., Hydra nodes) and Layer 3 (e.g., applications).
- Scope 1 and Scope 2 Emissions: It emphasizes accounting for direct (Scope 1) and indirect (Scope 2) emissions related to Layer 1 operations, aligning with standard carbon accounting frameworks.
- Role of Stake Pool Operators: Layer 1 functionality relies on Stake Pool Operators, making their energy use and emissions part of the methodology.
- Standardized Approach: The methodology aims to provide a transparent, consistent, repeatable process for calculating emissions, drawing on established carbon accounting practices.
- Importantly it should allow the Cardano community to discuss and control these impacts and help improve the data used to determine them

3.2 Essential infrastructure for Cardano layer 1: Cardano Stake Pools

While anybody can run a Cardano node by installing a full node wallet like Daedalus on a connected computer, it is the designated role of a Stake Pool operator to ensure that Cardano nodes are run 24/7 within certain parameters to ensure the network is fully operational. Therefore, it is the Stake Pools running the Layer 1 infrastructure and hence the Cardano Layer 1 Carbon Footprint is equivalent to the energy consumption of the combined number of Stake Pools.

The methodology will be grouped into the main GHG protocol categories Scope 1, Scope 2 and some examples on Scope 3 emissions as outlined in the Table 6 above.

The Cardano blockchain is tracking the number of Stake Pools and these are paid and controlled via the Ouroboros Proof of Stake protocol.

Parameter: Stake Pool (SPO) numbers

A key parameter to determine the Cardano footprint is the number of registered Cardano Stake Pools that maintain the blockchain. The more Stake Pools, the more decentralised and secure the blockchain is. However, each Stake Pool requires energy to run the Cardano network so this increased security causes additional carbon emissions.

- The *number of Stake Pools* is well monitored as each Stake Pool has to be registered and a registration fee paid.
- When looking at Stake Pool numbers and their associated carbon emissions it is important to consider key principles of Carbon Accounting, including completeness and accuracy. Such principles maintain credibility of carbon accounting of carbon emissions estimates should err on the side of caution by choosing estimates or methods that are likely to overestimate rather than underestimate emissions.
    - following these principles, each stake pool is assumed to use energy 24/7 and is required to do minimum maintenance
- Registered and retired pools are tracked through several Cardano explorers which means the number of Stake Pools is known for each epoch
    - Direct sources for live and in some cases historic pool numbers include:
        - Pool.pm
        - CardanoScan.io
        - Adapools.org
        - Pooltool.io
        - Adastat.net
- The 'total' pool number, which is the number of registered pools minus the number of retired pools, is usually reported on every explorer
- Additional Stake Pool numbers often also reported:
    - Active' Stake Pools or Stake Pools with 'Active Stake', with these usually around 10% lower including only pools with a minimum stake.
    - Total Pools accounting for all pools that are likely operational, ensuring all potential electricity consuming devices are included.

Table 7 below shows some types of pool numbers presented on public explorers to showcase activity of the network.

Table 7. **Variety of Stake Pool numbers presented on public explorers per epoch over time.**

Source	**Pool numbers, Epoch 484, 12 May 2024**	**Pool numbers, Epoch 540, 17 Feb 2025**
CardanoScan.io	Total Pools: 3117	Total Pools: 3005
Cexplorer.io	Total Pools: 3117	Total Pools: 3005
Pooltool.io	Total Pools: 3117 Active Pools: 2883	Active Pools (at least one lovelace staked): 2776
Adastat.net		Total Pools (excluding retired): 3005 Pools with Stake: 2783

Source	**Pool numbers, Epoch 484, 12 May 2024**	**Pool numbers, Epoch 540, 17 Feb 2025**
Total pool number for Carbon Accounting (highest reported figure):	**3117**	**3005**

As the number of Stake Pools changes over time because pools are added and retire, the Cardano energy consumption and its associated Carbon footprint also fluctuates. For this carbon accounting we have therefore used the average total stake pool numbers in 2024.

2024 Average Total Stake Pool Number (See Appendix A for analysis)

Carbon emissions accounting is done on an annual basis, and for the analysis in this work the **average number of Stake Pools in 2024 was determined as 3094 pools,** based on the mean of the total pool number in all epochs over the year.

Parameter: Energy consuming devices per Stake Pool

Practical Considerations for Stake Pool Operators on the number of Block Producers and relays for their set up

Every Stake Pool requires one Cardano node as a Block Producer and one relay as a minimum. However, there are a number of reasons to run at least 2 relays that are outlined below.

For current node versions, the minimum number of relays required to operate a Cardano Stake Pool remains one [42], ensuring basic connectivity between the block producer and the network. However, the recommended setup is two relays [43], a standard widely endorsed by the Cardano community to balance cost, security, and performance.

- Minimum (1 Relay): Viable for a basic setup but risky due to lack of redundancy and vulnerability to failure or attack [42]. Suitable only for experimental or low-stake pools.
- Recommended (2 Relays): The sweet spot for most SPOs, offering redundancy and improved reliability [43]. This is the practical standard for attracting delegators and ensuring stable operation, as outlined in established guides [44].
- More (3+ Relays): Ideal for larger, well-funded pools aiming for maximum uptime, global reach, and a competitive edge, though benefits taper off beyond a certain point.

The choice as an SPO should reflect the pool’s size, budget, technical capacity, and goals—whether prioritizing cost, reliability, or network contribution.

Three energy consuming devices per Stake Pool in 2024
The actual number of relays per registered Stake Pool changes in line with Stake Pool Operator preferences, but the above guidance for the recommended use of 2 relaysis what we have found stake pool operators commonly deploy. We have done an initial random survey of Cexplorer.io of 50 pools and found that on average they run 2 relays (see Appendix B for data).
This is also supported by the 2.1 relays per pool published in a 2024 CCRI report [45].

Energy consuming nodes per Stake Pool.

Every Stake Pool requires one Cardano node as a Block Producer and 2 Cardano nodes in 2 relays to connect to the network with reliability.

In conclusion, **the average 2024 Cardano Stake Pool runs 3 Cardano nodes**, 1 Block Producer and 2 Relays.

3.3. Scope 1 - Direct Cardano emissions

SPO onsite combustion – for heating or for energy generation

Scope 1 emissions of the blockchain are direct emissions generated by **operation and maintenance of the layer 1 blockchain and its layer 1 operators**. I.e. running on-site work spaces and/or servers i.e. any direct combustion from gas heating or generators or cars as utilised by node operators.

Most Stake Pool Operators heat their (home) office with gas
By analysing the locations hosting the majority of Cardano relays, we found that approximately 76% are situated in countries where gas boilers are the predominant heating method (see Appendix D). To estimate the carbon emissions associated with office heating, we assumed that the (home) offices of Stake Pool Operators are similarly distributed in those countries and that most operators therefore rely on gas to heat their workspaces. Consequently, while maintaining their pools, these operators generate direct emissions from their heating activities.

To determine the emissions associated with blockchain maintenance, we estimate the minimum time a Stake Pool Operator requires for maintaining their Stake Pool and then multiply it by a carbon factor for gas combustion.

Parameter: Carbon Factor for heating during homeworking

Over 80% of homes in the UK are heated by gas and the government provides a Carbon factor for gas heating for home working in the UK, which is 0.30234 kg CO2e per Full Time Equivalent Working hour for home working [46]. Therefore, to estimate the gas heating emissions for an individual working from home in the UK, we multiply the number of hours spent working by the Carbon factor.

To determine the associated direct carbon emissions for Cardano, we then estimated how much time a Stake Pool Operator spends on the minimum activities to maintain the Stake Pool. These minimum activities are:

Parameter: SPO work time for essential maintenance activities:

- Node updates happen on average about once a month
    - in 2024 the mainnet Cardano Node was updated 16 times
- KES (Key Evolving Signature) key rotation is needed at least every 90 days
- Monitoring nodes performance and uptime
- Migration of Cardano nodes onto different hardware depending on blockchain requirements
- Staying up to date with latest requirements and governance

SPO work time for essential maintenance activities
We estimated the time for essential maintenance activities to be **about 167 hours per year** (2024) per Stake Pool (see Appendix E).

Estimated Scope 1 emissions for Cardano Stake Pools

Based on the estimated 167 hours per year spent on essential maintenance per Stake Pool and the Carbon Factor for gas heating being 0.30234 kg CO2e per Full Time Equivalent Working hour the average pool generates approximately 50 kg of CO2e per year from combusting gas at home (Table 8).
To determine the Scope 1 emissions for the whole network, we multiplied this with the number of Stake Pool Operators of 3094, resulting in 156.2 tonnes of direct CO2e emissions per year (Table 8).

Table 8. Calculations for Scope 1 carbon emissions for Cardano Stake Pools.

(A) Average annual Scope 1 emissions per Stake Pool Operator in 2024	= Operator time * Home heating (gas) Carbon Factor per working hour = 167 h * 0.30234 kg per CO2e per working hour = **50.5 kg CO2e per Stake Pool**
(B) Annual Cardano Scope 1 emissions (2024)	= (A) * Number of Stake Pools = 50.5 kg CO2e * 3094 **= 156218.5 kg CO2 or 156.2 tonnes CO2**

Disclaimer: Note that the above is currently only a Scope 1 emissions estimate, and the data sources could be much further refined. Operator time has not currently been evaluated in great detail. Further operator survey data on an annual basis would be recommended to monitor impacts of blockchain upgrades on operator time and associated emissions, and to encourage Stake Pool operators to influence these direct emissions by switching to renewable energy sources.

3.4 Scope 2 - Indirect emissions from electricity use

Scope 2 emissions are Indirect emissions from purchased electricity, cooling or heating for the **operation and maintenance of the layer 1 infrastructure and its operators**. I.e. Stake Pool electricity consumption from the grid

Layer 1 purchased electricity for nodes and operator workstations

- *Stake pool hardware* needs to run a minimum of one block producing software node and one relay node, but the data on the actual number of relays, type of hardware and location is variable. Source of variability:

- Minimum hardware requirements for Stake Pool operation is recommended by the node developer and is stipulated as one block producer and one relay, with a certain amount of CPU power, storage and memory. In particular memory and storage requirements have increased over the years to allow for more functionality and a larger blockchain.
    - 2022 minimum system requirements (Source: https://iohk.zendesk.com/hc/en-us/articles/900001951586-Stake-Pool-Minimum-System-Requirements)

        - CPU: An Intel or AMD x86 processor with two or more cores, at 1.6GHz or faster (2GHz or faster for a stake pool or relay)
        - Memory: 16 GB of RAM
        - Storage: 75GB of free storage (100GB recommended for future growth)
        - Operating system: 64-bit Linux (i.e. Ubuntu Server 20.04 LTS)
        - Broadband: a good network connection and about 1 GB of bandwidth per hour

    - Recent requirements for servers running a Cardano node version 10.1.4: https://github.com/IntersectMBO/cardano-node/releases

        - An Intel or AMD x86 processor with two or more cores, at 1.6GHz or faster (2GHz or faster for a stake pool or relay)
        - Or, for MacOS, an Apple Silicon (M1, M2, M3 or M4) processor
        - 24GB of RAM
        - 200GB of free storage (250GB recommended for future growth)

- As estimated above in Section 3.2 the average Stake Pool runs 3 Cardano nodes (1 Block Producer and 2 relays) and each is run on its own independent environment requiring those minimum server criteria

- There are minimum hardware requirements to run a node, but the SPO community chooses different set-ups depending on what is important to them (the primary concern is to keep the node operational and not necessarily to save energy). From surveys and own experiences, a number of actual **computer hardware** set-ups are utilised
    - Data: Sustainability Survey with ~500 replies was completed in 2021, containing some hardware information, energy use, and more: https://docs.google.com/spreadsheets/d/1S5sZzoI9crz1ucEzBR6VmHQoMstC8b8CyRS7HQuw23Q/edit#gid=1350723574
    - **Baremetal servers -** types and energy consumption:
        - Low energy ARM computers, i.e Mac Mini (run at home) - can run on ~6W

- Standard home server, tower ~ 50W
- Rack servers - max of 168W
- Power consumption range 5.5W (low, Raspberry Pi) and 168W (high, Dell Poweredge R730), Source: https://ieeexplore.ieee.org/document/9741872 [18]

■ **Published Cardano Node electricity consumption**

Node electricity consumption Work by CCRI published in 2024 determined the **average node** (Block Producer and Relay Nodes) **electricity consumption** to be **25.5 W**, based on a mix of baremetal server setups running Cardano node software version 8.9.2 [32].

■ **Virtual or dedicated remote server infrastructures** (VPS) within server farms (i.e. Amazon web services or Google Cloud)

- Challenging task to estimate their energy use as they share resources, but such large server farms also usually require extra cooling. At this point we have no data to evaluate whether or not running your Cardano nodes on a VPS is more or less energy efficient. We initially presume it will be in a similar range to a baremetal server run in your home office.

■ **It is worth noting the Cardano blockchain runs on a mix** of baremetal and VPS, often with at least one relay in the cloud to improve security of service (https://cexplorer.io/relays)

Estimated combined Electricity Consumption of Stake Pool Operator Cardano Nodes

Based on the total number of nodes running the Cardano network and the estimated electricity consumption of each individual node, the network's total power consumption and annual electricity usage are calculated as detailed in Table 9. These figures serve as the basis for Scope 2 carbon accounting.

Table 9. Calculations to estimate electricity consumption of Cardano nodes.

(C) Cardano node network power consumption (2024) [W or kW]	= Number of Stake Pools *Average number of nodes per stake pool* Average electricity consumption per node = 3094 * 3 * 25.5 W = **236691 W or 236.7 kW**
(D) Annualised Cardano Node electricity consumption (2024) [kWh]	= (C) * 24h * 365 days = 236.7 kW * 24h * 365 **= 2073413.2 kWh per year**

Electricity consumption of Stake Pool Operators for essential maintenance

While Cardano nodes are the main electricity user of the blockchain, Stake Pool Operators do use electricity for home computers, lighting and other office equipment while running pool maintenance.

For home office power consumption, UK carbon factor statistics for 2024 estimated an average power use of 150W per person for a workstation with a laptop or PC, monitor, phone, printer including 10W for lighting. [1]

Similarly to the above node electricity consumption, for the electricity consumption of the Cardano Stake Pool Operators we multiplied the number of Stake Pools with the time estimated a Stake Pool Operator attends to Stake Pool maintenance and multiplied it by 150W to determine an estimate for the power consumption and further the annual electricity consumption (Table 10).

Table 10: Calculations of estimated annual Cardano Operator office electricity consumption

(E) Cardano Operator network power consumption (2024) [W or kW], note this would be the power consumption if all SPOs work at the same time	= Number of Stake Pools * Work time * Average electricity consumption of Operator workstation = 3094 * 150 W = **464100 W or 464.1 kW**
(F) Annualised Cardano Operator electricity consumption (2024) [kWh]	= (E) * 167h **= 77504.7 kWh per year**

Location-based method to determine Scope 2 Carbon emissions from Electricity consumption

The location based method reflects the average emissions intensity of grids on which energy consumption occurs (using mostly grid-average emission factor data). Therefore, the method requires the amount of electricity consumed at each location as well as the respective grid-average emission factors which are often published by state authorities.
Ref: Greenhouse Gas Protocol, Scope 2 Guidance (2015)

- Country location and associated grid carbon emissions factors:
    - The location of a majority of relays is publicly available through blockchain explorer [47] - https://cexplorer.io/relays
      Note: Due to the ability of operators to run 'dark' servers/nodes it is not possible to determine the location or energy supply for all node servers
    - Carbon Emissions factors for each country are available online
        - i.e. from IEA (paid service) or Our World in Data (free) [48] (https://ourworldindata.org/grapher/carbon-intensity-electricity)

Relay-location based carbon emissions factor for Cardano electricity

Using the available information on relay locations of the Cardano Network [47], and 2023 national grid carbon factors for these nations [48], we calculated the relay location weighted carbon emissions factors for Cardano as shown in Appendix F.

Relay location weighted Carbon Emissions Factor for Cardano
The Carbon Intensity of the **average electricity of Cardano Stake Pool Operators has been calculated as 0.3337574526 kg CO2/kWh**. See calculation in Appendix F.

Estimated Cardano Scope 2 emissions from electricity consumption

Based on the above research and previously published work (see Appendix C) using a location-based method, electricity consumption was multiplied with the carbon intensity factor to calculate the Cardano Scope 2 emissions (Table11).

Table 11. Calculating Scope 2 Emissions from Cardano Layer 1 electricity use

(G) Scope 2 - Annual Cardano Carbon Emissions from node electricity (2024)	= (Annual node electricity consumption (D) * Cardano weighted carbon emissions factor = 2079320.25 kWh * 0.3337574526 kg CO2/kWh = 693.9886318 tonnes CO2 per year
(H) Scope 2 - Annual Cardano Carbon Emissions from Operator home electricity use (2024)	= SPO work time for essential maintenance * Number of Stake Pools * 150 W * Cardano electricity carbon factor = 167.8h * 3094 Stake Pools * 0.15kW * 0.333757 kg CO2/kWh = 25.9 tonnes CO2 per year
(I) Combined Scope 2 emissions from Cardano Layer 1 electricity use	= (G) + (H) **= 719.978 tonnes CO2 per year**

Impact of using electricity from renewable sources on carbon accounting

In 2021, 33% of Stake Pool Operators (SPOs) reported operating on renewable energy. SPOs have the option to either purchase renewable energy or generate it themselves to further reduce their carbon emissions. A survey conducted by Input Output in April 2021, with 354 participating pools, found that 33.8% of these pools claimed to power their infrastructure using renewable energy sources such as wind, solar, or hydropower (https://input-output.typeform.com/report/ifq5D45Y/8aDT9otbSb2b743L).

However, carbon accounting standards do not easily allow for reductions in reported emissions without substantiated evidence. Certification and auditing would be necessary to recognise such reductions, a process that is currently challenging to implement across the Stake Pool Network. As the existing survey data relies on self-reporting and assumes a complete understanding of electricity supply chains, it has not been factored into this carbon accounting exercise to avoid underestimating emissions.

This raises a key question: how can the use of renewable energy be verified across a decentralised network of small operators?

Future Possibilities
Looking ahead, it is conceivable that renewable electricity purchased by operators could be directly certified by producers via blockchain technology. This would provide verifiable evidence and generate auditable data on renewable energy usage, which could then be incorporated into calculations of the Cardano Blockchain's carbon emissions.

3.5 Combined Scope 1 and Scope 2 Carbon Emissions of the Cardano Blockchain

Carbon accounting traditionally prioritises Scope 1 and Scope 2 emissions because they represent the direct and immediate environmental footprint of an organization's operations—emissions from owned or controlled sources (Scope 1) and those tied to purchased electricity, heat, or steam (Scope 2). Unlike Scope 3 emissions, which encompass a broader, often more complex web of indirect emissions across value chains, Scope 1 and 2 offer a tangible starting point with well-established methodologies and data availability.

Table 12: Combined Annual Scope 1 and 2 emissions of the Cardano blockchain

(J) Combined Scope 1 & 2 emissions for the Cardano Layer 1 blockchain for 2024	= (B) + (I) = 156.95 tonnes CO2 + 719.9 tonnes CO2 **= 876.93298 tonnes CO2 per year**

Up to here this white paper has introduced the concept of carbon emissions and why it is important to account for them. It has laid out which parts of the blockchain are appropriate to include into the accounting, identified the data and calculated the controlled emissions of the Cardano Blockchain in 2024. We will finish by briefly highlighting Scope 3 emissions, which may be included in future strategies for estimating the carbon footprint of the Cardano ecosystem.

3.6 Scope 3 - Indirect emissions upstream and downstream of layer 1

Scope 3 emissions encompass indirect emissions arising from activities associated with the Cardano blockchain, yet they fall outside the direct control of Layer 1 blockchain operators. These emissions can occur upstream or downstream of the Cardano Layer 1 blockchain.

Upstream factors, such as internet infrastructure and power generation, and downstream elements, including Layer 2 and 3 solutions, applications, and user activities, are not managed by nodes or node operators and thus are excluded from this Layer 1 emissions calculation. Consequently, these upstream and downstream impacts are classified under the indirect, non-controllable Scope 3 category—emissions resulting from blockchain-related activities.

While Scope 3 falls beyond the focus of this work, Section 2.5 provides an overview of what may be considered Scope 3 emissions, with examples of relevant upstream and downstream emissions outlined below.

Example Upstream emissions

Footprint of internet hardware and home computer

- Emissions from production of computer hardware
- Router power consumption ~ 2-20W, Source: https://www.thehomehacksdiy.com/how-much-electricity-power-does-a-wi-fi-router-use/
- Some SPOs also use Starlink satellite connection (~100W)

Cardano emissions from directly related infrastructure and companies:

Whether or not these key Cardano related companies and functions should be part of the Cardano Carbon Footprint, is discussed above in Section 2.3:

- Cardano Foundation (Company reporting)
  - requires company to report corporate emissions as per GHG protocol
- Input Output (Company reporting)
  - requires company to report corporate emissions as per GHG protocol
  - Catalyst management – Input Output +
  - Other Cardano Governance impacts

Example Downstream emissions

Projects building on Cardano i.e. Layer 2 and Layer 3

- Hydra (Layer 2)
- Cardano Wallets or any Apps (Layer 3)

Life cycle emissions of computer hardware

- Emissions from recycling and/or final disposal of computer hardware
  - Some initial calculations for Cardano have been provided by CCRI in ref [45]

3.7 Proposal: Applying a 20% Uplift to ensure completeness

Whenever the Pond Foundation calculates carbon emissions in accordance with the ISO14064-1 standard, a 20% uplift to the final calculated emissions is applied. They do this to ensure they don't underestimate member's yearly carbon emissions.

The data used, while based on scientific papers and approved emissions factors, are nonetheless estimates. The 20% helps ensure emissions are on the right side of any variations.
Calculating carbon emissions is an imprecise science, which is why ISO has developed the ISO14064-1 standard. This standard ensures there is a clear, standard approach that allows comparisons between organizations and from period to period, e.g., from year to year.

Pond Foundations emissions calculations using this 20% uplift have been verified as complying with ISO14064-1 and as such, we as the authors of this white paper strongly recommend that a 20% uplift is applied to the calculated Scope 1 and 2 emissions for Cardano Layer 1.

Table 13: Annual Scope 1 and 2 emissions of the Cardano blockchain including 20% uplift

Combined Scope 1 & 2 emissions for the Cardano Layer 1 blockchain for 2024 including a 20% Uplift	= (J) * 1.2 = **1052.3195 tonnes CO2 per year**

Acknowledgment

I, Christian Unger, am privileged to present this white paper on the carbon footprint of the Cardano blockchain, a project sparked and shaped by the collaboration of many, to whom I extend my deep gratitude. Hamish Cunningham and I, both Stake Pool Operators at SHIFT, launched this initiative together to advance environmental sustainability and position Cardano as one of the most eco-friendly blockchains.

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We apologize for the delays in this publication, which arose from the research's complexity, our dedication to safeguarding our climate, the need for further learning, and personal and environmental commitments.

Hamish and I warmly invite ADA holders to connect with us and, if possible, support this effort by delegating to SHIFT Pool or our active CNC Alliance Pools.

Thank you.

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Appendix A: 2024 stake pool numbers

Total Stake Pool number per epoch in 2024 incl average:

Epoch	Month	AdaStats Total Pools minus Retired Pools; https://adastat.net/epochs?page=2
458	January	3111
459	January	3112
460	January	3110
461	January	3115
462	January	3117
463	January	3115
464	January	3114
465	February	3112
466	February	3108
467	February	3107
468	February	3104
469	February	3100
470	February	3094
471	March	3095
472	March	3099
473	March	3094
474	March	3096
475	March	3086
476	March	3084
477	April	3085
478	April	3092
479	April	3095
480	April	3096
481	April	3101
482	April	3111
483	May	3112
484	May	3119
485	May	3120
486	May	3120
487	May	3119
488	May	3115
489	June	3112
490	June	3112
491	June	3110
492	June	3110
493	June	3108
494	June	3109
495	July	3108
496	July	3109
497	July	3110
498	July	3112
499	July	3111
500	July	3109
501	August	3106
502	August	3101
503	August	3102
504	August	3099
505	August	3098
506	August	3094
507	September	3095
508	September	3094
509	September	3095
510	September	3092
511	September	3092
512	September	3093
513	October	3084
514	October	3081
515	October	3079
516	October	3080
517	October	3079
518	October	3079
519	October	3079
520	November	3073
521	November	3071
522	November	3069
523	November	3065
524	November	3063
525	November	3059
526	December	3049
527	December	3049
528	December	3036
529	December	3037
530	December	3039
531	December	3016
Average for 2024		**3093.594595**

Appendix B: Relay numbers per pool

Relay Survey of 50 random Stake Pools					
Stake Pool Ticker	Relay number	Source:	https://cexplorer.io		
ANIM	2				
MARAC	3				
AMS	1				
ECO	3				
XORN	2				
SMILE	1				
SEA	2				
AZUR2	2				
ADEN	1				
WOOF	2				
ASTRA	2				
YOON	2				
KAYA	1				
DOLCA	1				
BLADE	1				
1STEP	2				
IDEAL	1				
888	4				
AA1	2				
PUNKR	3				
SAGAN	2				
COPI	2				
DAVE	1				
CHG	2				
JUNO	4				
NEWMX	1				
RADAR	2				
FAIR	4				
LIDO	2				
1COMM	3				
STKGR	2				
CHEF	8				
CORAL	1				
F4ADA	2				
ANP	5				
SAKE	2				
AUSST	2				
RELAY	1				
QXT	2				
BLC	2				
ADAHR	2				
BCSH1	1				
ATAD2	3				
DARK	1				
BROCK	1				
STR8	2				
SUNNE	2				
SMAUG	1				
EUADA	1				
Average relay number	**2.081632653**				

Appendix C: Variability of Scope 2 carbon accounting in published work

Cardano electricity consumption and Scope 2 footprint variability based on input and method variability

References incl Inputs and Results

		Inputs							Results					
Org/ Source	**Year**	**# of Stake Pools**	**# nodes per pool**	**# electricity consuming servers/Nodes**	**Consumption per node [kW], mean, median or best guess**	**Consumption per node in the cloud [kW]**	**Carbon intensity factor [kg CO2/kWh]**	**Nodes running on renewable energy [%]**	**Global electricity consumption [kW]**	**Annual electricity consumption**	**Annual energy consumption [MWh]**	**Scope 2 emissions, without considering renewables [t**	**Scope 2 emissions, considering renewables [t**	**Reference**
CNC	2021	2842	4	11368	0.10125	n/a	0.4073	33.80%	1151.01	10082847.6	10082.8476	4106.743827	2718.664414	49
UCL	2021	2958	1	2958	0.0868	n/a	n/a	n/a	256.7544	2249168.544	2249.168544	n/a	n/a	18
CCRI	2022	3002	1	3002	0.0227	n/a	0.475	n/a	68.1454	598755	598.755	284.408625	n/a	28
UCL	2023	1209	1	n/a	0.044185	n/a	n/a	n/a	142.63	1249438.8	1249.4388	n/a	n/a	19
CCRI	2023	n/a	n/a	3177	0.0353	n/a	0.365	n/a	112.1481	982417.356	982.417356	358.5823349	n/a	32
CCRI	2024	1049	3	3147	0.025576	n/a	0.356	30.88	80.487672	705072.0067	705.0720067	251.0056344		45

Appendix D: Relay locations per country

Relay location countries (Cexplorer, Feb 2025)	**Percentage (based on stake); https://cexplorer.io/relays , 16/02/2025**	**Relay number (https://cexplorer.io/relays, 16/02/2025)**	**Main type of heating per country ****	**Relays in mainly gas heated countries**	**Source: International Energy Agency (IEA). "World Energy Statistics and Balances 2023." Accessed February 19, 2025. https://www.iea.org/data-and-statistics.
Germany	25.10%	832	Gas	832	
United States	20.30%	794	Gas	794	
United Kingdom	8%	167	Gas	167	
Canada	6.30%	170	Gas	170	
France	4.94%	116	Electric		
Netherlands	4.51%	124	Gas	124	
Japan	4.01%	136	Heat pumps		
Ireland	3.38%	37	Oil		
India	3.02%	47	Biomass		
Finland	3.01%	95	Distric heating		
Sweden	2.93%	41	Distric heating		
Singapore	2.26%	77	Gas	77	
South Korea	1.89%	56	Gas	56	
Australia	1.52%	51	Gas	51	
Poland	1.42%	23	Coal		
Austria	1.25%	29	Distric heating		
Switzerland	1.01%	29	Heat pumps		
Brazil	0.67%	8			
UAE	0.57%	6			
Lithuania	0.57%	11			
Hong Kong	0.52%	11			
Belgium	0.42%	12			
South Africa	0.41%	9			
Romania	0.28%	7			
Norway	0.27%	7			
Vietnam	0.27%	16			
Latvia	0.17%	3			
New Zealand	0.16%	4			
Italy	0.15%	16			
Spain	0.12%	11			
Chile	0.11%	4			
Indonesia	0.10%	3		Sum:	
Total	**99.64%**	**2952**	#	**2271**	
				Percentage of relays in mainly gas heated countries:	
				76.93%	

Appendix E: Estimated Operator time for essential Stake Pool maintenance

Essential Operator Time spend maintaining Cardano nodes - Layer 1

Table1

Tasks to maintain Cardano node	# hours per year	Note	Source
Initial install and set up	n/a	Only one off and not included into normal maintenance time	
Upgrade Cardano Node	48	hours	Table 1
Monitoring Nodes, managing relay nodes and security	60.809	Average 10min per day, over year	Estimate
Rotate KES keys (minimum every 90 days)	4	1h Every 90 days	Estimate
Test updates on Testnet	n/a	Testnet activity not included, as not a requirment	
Migration of hardware/servers as required	5	Once per year, depending on blockchain size, node software requirments and orginal hardware capacity (hard drive size)	Estimate
Stay up to date on latest Cardano updates, Governance, ensure compliance	50	1 hour per week	Estimate
Stake Pool Marketing	N/A	is excluded as not considered essential for L1 maintenance	
Total	**167.809**	**hours**	

SPO time spend on node upgrades per year

Node upgrades per year	16	See table 1 for all mainnet upgrades	Table 1
Hours per pool upgrade (3 nodes; Average time between beginners and experts)	3	For an average pool operator, not a total beginer and not a absolute pro	Estimate based on own experience and surveying of CNC pool operators
Number of hours spend on node upgrades	48	Number of node upgrades multiplied by time required per upgrade.	Calculation

Table 1

2024 Cardano MAINNET Node releases	Source: https://github.com/IntersectMBO/cardano-node/releases	#
Jan	8.7.3	1
March	8.9.0	2
	8.9.1	3
April	8.9.2	4
May	8.9.3	5
June	8.9.4	6
	8.12.1	7
	8.12.2	8
July	9.0.0	9
	9.1.0	10
Sep	9.1.1	11
	9.2.0	12
	9.2.1	13
Oct	10.1.1	14
Nov	10.1.2	15
	10.1.3	**16**

Appendix F: Cardano Relay locations and associated carbon factors

Location Based Carbon Factor weigted by Relay locations:

Cardano Relay Location-based Electricity Carbon Factor	0.3337574526	kg CO2/kWh	See below calculations based on weighted country location carbon factors

*Source: https://cexplorer.io/relays

**Source: https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table

Data table - Grid carbon factors and relay locations

Relay location countries (*Cexplorer, Feb 2025)	*Percentage (based on stake); 16/02/2025	***Relay number, 16/02/2025**	Country group designation	**National grid carbon factors (2023)	Unit	Carbon Factor multiplied by relay numbers	
Germany	25.10%	832	OECD	0.381	kg CO2/kWh	316.992	
United States	20.30%	794	OECD	0.369	kg CO2/kWh	292.986	
United Kingdom	8%	167	OECD	0.238	kg CO2/kWh	39.746	
Canada	6.30%	170	OECD	0.17	kg CO2/kWh	28.9	
France	4.94%	116	OECD	0.056	kg CO2/kWh	6.496	
Netherlands	4.51%	124	OECD	0.268	kg CO2/kWh	33.232	
Japan	4.01%	136	OECD	0.485	kg CO2/kWh	65.96	
Ireland	3.38%	37	OECD	0.291	kg CO2/kWh	10.767	
India	3.02%	47		0.713	kg CO2/kWh	33.511	
Finland	3.01%	95	OECD	0.079	kg CO2/kWh	7.505	
Sweden	2.93%	41	OECD	0.041	kg CO2/kWh	1.681	
Singapore	2.26%	77		0.471	kg CO2/kWh	36.267	
South Korea	1.89%	56		0.431	kg CO2/kWh	24.136	
Australia	1.52%	51	OECD	0.549	kg CO2/kWh	27.999	
Poland	1.42%	23	OECD	0.662	kg CO2/kWh	15.226	
Austria	1.25%	29	OECD	0.111	kg CO2/kWh	3.219	
Switzerland	1.01%	29	OECD	0.035	kg CO2/kWh	1.015	
Brazil	0.67%	8		0.098	kg CO2/kWh	0.784	
UAE	0.57%	6		0.658	kg CO2/kWh	3.948	Source: https://ember-energy.org/countries-and-regions/middle-east/
Lithuania	0.57%	11	OECD	0.16	kg CO2/kWh	1.76	
Hong Kong	0.52%	11		0.582	kg CO2/kWh	6.402	Used China Carbon Factor on Our World In Data
Belgium	0.42%	12	OECD	0.138	kg CO2/kWh	1.656	
South Africa	0.41%	9		0.708	kg CO2/kWh	6.372	
Romania	0.28%	7		0.241	kg CO2/kWh	1.687	
Norway	0.27%	7	OECD	0.03	kg CO2/kWh	0.21	
Vietnam	0.27%	16		0.475	kg CO2/kWh	7.6	
Latvia	0.17%	3	OECD	0.123	kg CO2/kWh	0.369	
New Zealand	0.16%	4	OECD	0.113	kg CO2/kWh	0.452	
Italy	0.15%	16	OECD	0.331	kg CO2/kWh	5.296	
Spain	0.12%	11	OECD	0.174	kg CO2/kWh	1.914	
Chile	0.11%	4	OECD	0.291	kg CO2/kWh	1.164	
Indonesia	0.10%	3			kg CO2/kWh	0	
Total percentage of relays	**99.64%**						
		2952	**Relay-Location-Weighted Carbon Factor**	**0.3337574526**	kg CO2/kWh	985.252	