Measuring the Impact of the Green Mining Initiative

Crypto Carbon Ratings Institute (CCRI)
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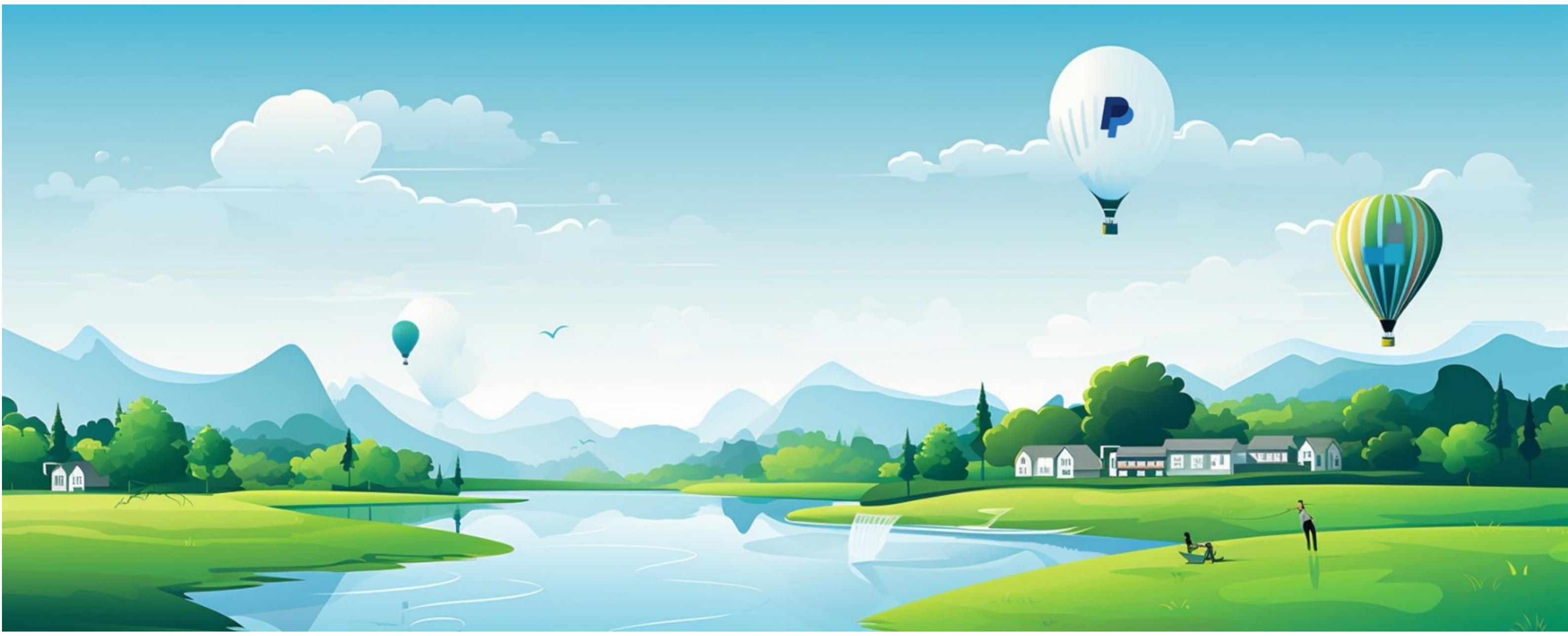

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1. Introduction

Bitcoin mining is known for its high energy consumption. In the Bitcoin network, so-called miners compete to solve a computational puzzle to add new blocks to the chain. The purpose of adding blocks is to validate coin ownership and transactions included in the blocks. To participate in the competition, miners run specialized hardware devices which consume energy. Depending on the energy source, the mining activity translates into carbon emissions – which may have adverse impacts on our climate.

PayPal's Blockchain Research Group, in a strategic collaboration with Energy Web and DMG Blockchain Solutions Inc., has developed an incentive mechanism to encourage Bitcoin miners to use low-carbon energy sources. In the first step, miners that want to participate in this Green Mining Initiative (GMI) need to obtain accreditation from Energy Web, which audits Bitcoin miners' energy sources. Subsequently, on-chain transactions by GMI users are routed to accredited green miners. To ensure the transactions are validated by green miners only, the transactions are broadcasted with very low transaction fees and an additional BTC reward locked in a multisig payout address that can only be claimed by green miners (see here for further details).

The GMI subsidizes miners that use clean energy sources to run their operations and incentivizes other miners to switch to clean energy sources or ideally invest in additional renewable energy generation resources, such as wind and solar PV. Block rewards and transaction fees determine overall mining activities and associated carbon emissions. The sum of both revenue streams determines miners' income and represents the upper limit they can spend on hardware and energy to run their operations. In the past, block rewards were the main source of miners' income. However, with each Bitcoin halving, the share of income from transaction fees increases (ceteris paribus; unless the Bitcoin price increases in the about four years between two halvings and/or a respective decrease in transaction fees overcompensate the effect). Therefore, we expect that transaction fees will become the main source of miners' income in the long run – and the GMI offers an effective mechanism to target this revenue stream and nudge miners via economic incentives towards clean energy sources. The average share of transaction fees in overall miner rewards year-to-date 2024 is 8% up from 6% on average in 2023.

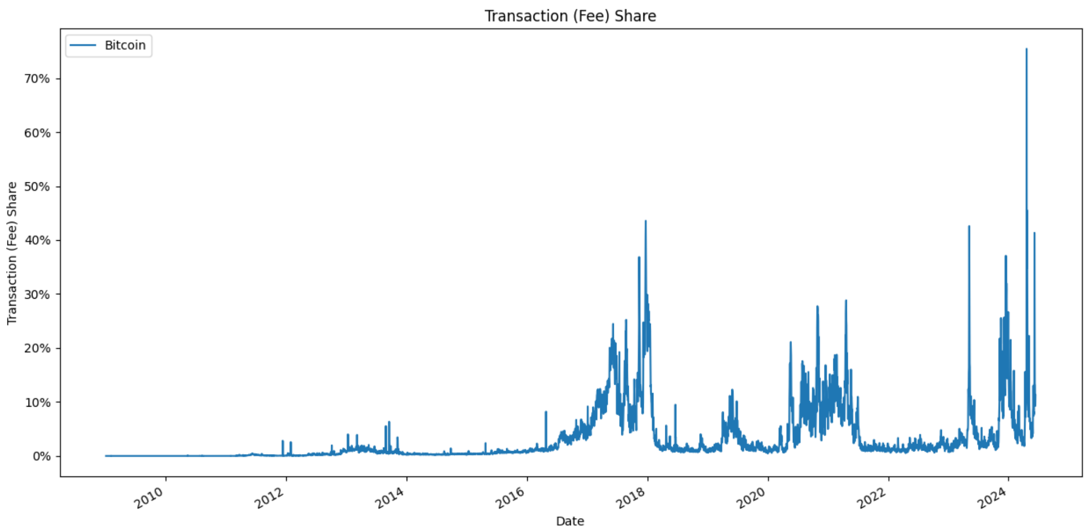

Figure 1: Share of Bitcoin transaction fees in overall mining rewards (sum of block reward + transaction fees) Source: CCRI research.

The following section provides background information on crypto-related climate impacts and how to measure and account for them. Section 3 introduces the framework to determine the climate impact of the GMI. Section 4 concludes and provides an outlook with avenues for future research.

2. Background

At the time of writing in April 2024 (post the fourth Bitcoin halving), we estimate that Bitcoin mining causes 88 million metric tonnes of carbon dioxide ($MtCO_2$) annually. After Ethereum switched its consensus mechanism from proof-of-work (PoW) to proof-of-stake (PoS) in 2022, Bitcoin has continued to be the largest emitter among blockchain networks by far, causing 37x more emissions than the second-highest emitter (Dogecoin). Figure 2 charts the increase of Bitcoin's carbon footprint since its inception less than two decades ago, and highlights its dominant share in total blockchain network emissions. The chart also shows Ethereum's carbon footprint, which dropped by over 99.9% after "The Merge" in 2022 (for details, please see here).

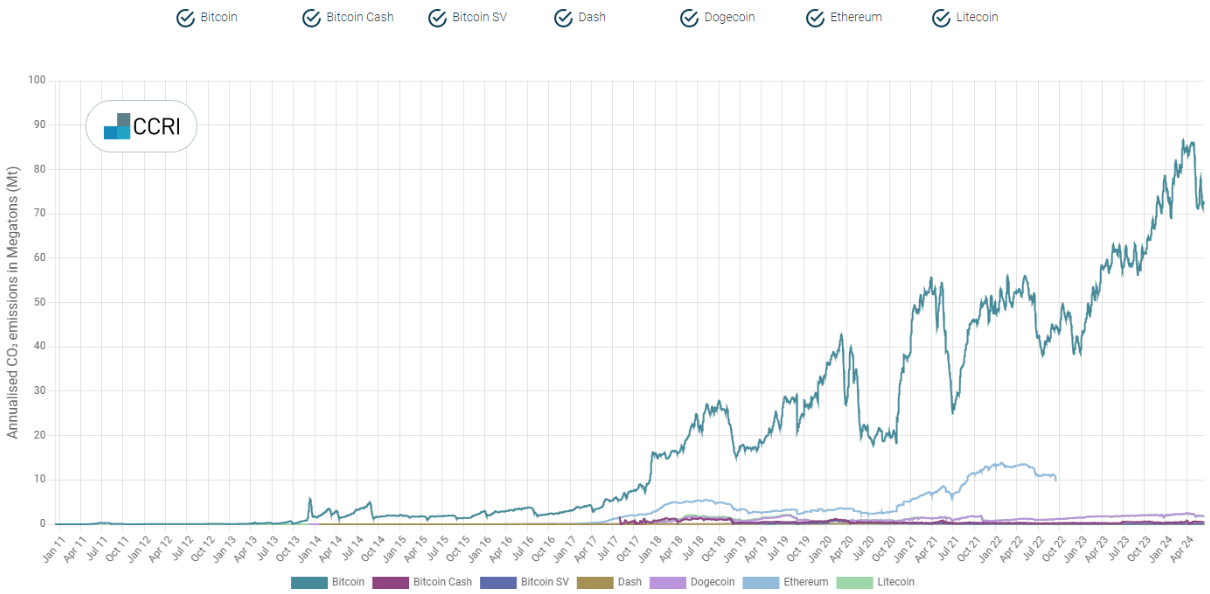

Figure 2: Annualized CO_2 emissions of proof-of-work cryptocurrencies. Source: https://indices.carbon-ratings.com/

To quantify the energy consumption of PoW blockchain networks, two approaches have evolved.

- **The top-down approach** was populated by Alex de Vries' Digiconomist Bitcoin Energy Consumption Index. It assumes that the money earned by miners is directly invested, to a certain degree, into energy. With data available on the miners' income (consisting of block rewards and transaction fees), the exchange rate for Bitcoin, and the assumption that a predefined share of income is spent on energy, it is straightforward to calculate the respective monetary value of energy. With an assumption regarding the average electricity price, the total network energy consumption can be calculated on a daily basis.

- **The bottom-up approach** was initially developed in (Krause & Tolaymat, 2018), refined in (Stoll, Klaaßen, Gallersdörfer, 2019) and is now used in the most-cited Cambridge Bitcoin Energy Consumption Index. Instead of starting with miners' income, the bottom-up approach considers the network hash rate to be the main driver of energy consumption. The approach resorts to a list of available hardware devices, their power demand, and hash rate as input parameters. For a given electricity price, we can filter this list of profitable devices. The profitable devices can then be weighted according to their age and availability in the market, thus providing an estimate for all hardware devices that are up and running at a given point in time. This hardware picture allows for calculating the daily power demand, and thus, the total annualized energy consumption of the network.

Subsequently, for both approaches, emission factors can be used to translate the energy consumption into carbon emissions. For instance, CCRI uses emission factors from the Environmental Protection Agency for U.S. states, from the Environmental Energy Agency for European countries and from Climate Transparency for all other G20 countries.

It is noteworthy that Bitcoin proponents, industry associations, and the first academic studies on the subject highlight potential climate benefits of mining from power grid balancing services [1–3], renewable energy expansion [4–8], methane emission reductions [9,10], and heat recovery.[11] Our research suggests, however, that the energy-related climate costs of Bitcoin mining currently far outweigh such benefits.[12]

For crypto stakeholders, the key question is how to account for their individual responsibility. As mentioned above, block rewards and transaction fees determine overall mining activity. Consequently, it is vital to allocate a fair share of the total network carbon footprint to both emission drivers. CCRI together with South Pole and in consultation with PayPal published a framework in 2022 to support crypto value chain stakeholders in allocating carbon emissions to their activities based on their cryptocurrency-related holdings and transactions.

Beyond the individual GHG inventories, the GMI has also implications for Bitcoin's network carbon footprint and potentially total global emissions. In the next Section, we provide a framework to determine the climate impact of the GMI through three different lenses.

3. Framework to measure the impact of the GMI

Here we propose a framework to evaluate the climate benefits of the GMI. The framework differentiates three lenses through which we determine the climate impact the GMI might bring. The three lenses are GMI users' GHG inventories, the Bitcoin network's carbon footprint, and overall carbon emissions.

GMI users' carbon footprint

Leveraging green miners for transaction validation has a direct impact on GMI users' corporate Scope 3 emissions. Already in the short term, knowing that transactions have been validated by a green miner may be factored in during the carbon accounting process. For instance, a single Bitcoin transaction caused 40kg of CO_2 as of April 2024 (source: CCRI API). Accounting for the reduced emissions caused by green miners may therefore be used to reduce respective emission allocations from transactions. Looking at the equation of the original Crypto Climate Impact Accounting Framework (by CCRI and South Pole in consultation with PayPal), we may amend the formula as follows:

- **Original Crypto Climate Impact Accounting Framework:**

$$\text{Crypto user carbon footprint} = \text{Total network emissions} \times \left(f \, \frac{\text{Number of coin held}}{\text{Total supply of cryptocurrency}} + (1-f) \, \frac{\text{Transaction fee paid}}{\text{Total network transaction fees}} \right)$$

f The factor f is the **share** of the **block reward** of the **overall reward** the miner receives

1-f The factor (1-f) is the **share** of the **transaction fee** of the **overall reward** the miner receives

User-specific data

Blockchain network data

Overall reward for validators/miners = block reward + transaction fee

- **Extended Crypto Climate Impact Accounting Framework:**

$$\text{GMI user carbon footprint} = \text{Total network emissions} \times f \, \frac{\text{Number of coins held}}{\text{Total supply of cryptocurrency}} + g \, \text{Number of GMI transactions}$$

g The factor g is the **average amount of carbon** caused by one **GMI transaction** (as miners that qualify for Energy Web's Green proofs may still use some emitting energy sources)

The Extended Crypto Climate Accounting Framework considers the average amount of carbon emissions caused by one GMI transaction (g). If all miners participating in the GMI were to mine exclusively based on carbon-free energy sources, g would be zero and there would not be any emission arising from transactions (although the emissions arising from coin holdings would still prevail as the first part of the equation is not affected by "g". Still, the "g" factor warrants further investigation, as it is likely that not all miners participating in the GMI will only use carbon-free electricity. To establish a better understanding of how th "g" factor may look like, we define four exemplary miners:

- GMI miner 1: using 97% carbon-free sources[1]
- GMI miner 2: using 75% carbon-free sources
- GMI miner 3: using 55% carbon-free sources
- GMI miner 4: using 40% carbon-free sources

[1] This figure is based on the public available Clean Energy Score of DMG which is to this date the only mining company that publish its Clean Energy Score (= share of carbon-free energy sources) as part of the «Green proofs for Bitcoin» program run by Energy Web.

We assume that the remaining energy sources are equal to the global distribution of fossil-fueled-based electricity production resulting in a carbon intensity of 803 g CO2e/kWh.[2] In the next step, we define three scenarios which assume different weightings of the exemplary miners in the GMI. Depending on the scenario, we calculate a relative emission reduction for each GMI transaction between 95% and 46% compared to the average carbon intensity per regular Bitcoin transaction which sits at 494 g CO2e/kWh as of May 2024.

Scenario 1 - *only high scoring miners in GMI*	
Weight of miners in GMI	
GMI miner 1	100%
GMI miner 2	0%
GMI miner 3	0%
GMI miner 4	0%
Average carbon intensity per GMI tx [g CO2e / kWh]	27
Average carbon intensity per regular BTC tx (as of May 2024) [g CO2e / kWh]	494
Relative emission reduction for each GMI tx	**95%**

Scenario 2 - *mix of miners certified via Clean Energy Score (>50% carbon free sources)*	
Weight of miners in GMI	
GMI miner 1	33%
GMI miner 2	33%
GMI miner 3	33%
GMI miner 4	0%
Average carbon intensity per GMI tx [g CO2e / kWh]	196
Average carbon intensity per regular BTC tx (as of May 2024) [g CO2e / kWh]	494
Relative emission reduction for each GMI tx	**60%**

Scenario 3 - *mix of miners also scoring below Clean Energy Scores threshold (>50% carbon free sources)*	
Weight of miners in GMI	
GMI miner 1	25%
GMI miner 2	25%
GMI miner 3	25%
GMI miner 4	25%
Average carbon intensity per GMI tx [g CO2e / kWh]	268
Average carbon intensity per regular BTC tx (as of May 2024) [g CO2e / kWh]	494
Relative emission reduction for each GMI tx	**46%**

Figure 3: Relative emission reduction for each GMI transaction per scenario

It is noteworthy that in case total network emissions remain constant, broadcasting transactions with very low transaction fees would increase the share of regular transaction fees in total transaction fees. At the same time, the reduction of total network transaction

[2] The global fossil-fueled-based electricity production distribution (59% coal, 37% gas, 4% oil) is taken from OurWorldinData. Life Cycle Emissions Factors for Electricity Generation Technologies are taken from NREL.

fees would also decrease miner rewards from this component (1-f), and therefore, increases emission allocations to coin holdings (f).[3]

The extended Crypto Climate Impact Accounting Framework assumes that 100% of the transactions are routed to green miners. If a GMI user routes also some transactions to non-green miners, it is important to account for those using the second factor of the original framework. Translating the additional costs for GMI users from green miner subsidies to CO_2 abatement costs may be one avenue to quantify and compare the climate impact of the GMI. Considering the emission caused by each Bitcoin transaction, by using the GMI, entities such as PayPal may reduce their carbon emissions by about 40kg per transaction as of April 2024. Assuming a carbon price of $100/tonne – this reduction translates into a benefit of $4 per transaction. This approach also offers a mechanism to link the green premium to a dynamic reference carbon price index to achieve effective emission reductions.

Bitcoin's network carbon footprint

Incentivizing green miners may also support the decarbonization of the Bitcoin network as a whole. The revenue of Bitcoin miners usually consists of block rewards and transaction fees. The GMI offers an additional revenue stream to miners symbolized by *GMI tx revenue* in the equation if they fulfill the requirements of the GMI and decide to participate.

Overall miner revenue = Block reward + Tx fee + GMI tx revenue

GMI tx revenue This revenue stream is optional if miners partcipcate in the GMI.

The GMI tx revenue is driven by two factors: the number of GMI tx rewards that the miner can successfully claim as well as the amount of GMI tx reward per transaction. If the entire GMI tx revenue of an eligible miner surpasses the setup cost to participate in the GMI, it would be rational for a miner to do so. If the entire GMI tx revenue of a non-eligible miner (not enough carbon-free energy used) surpasses the setup cost to participate in the GMI as well as the cost to switch its operations to carbon-free energy sources, it would be rational for a miner to do so. If miners switch to clean energy sources, the carbon intensity of the network and ceteris paribus its carbon footprint decreases. Consequently, not only the share of emissions allocated to transactions but also the share of coin holders decreases. The higher the share of energy sources that is switched from fossil-fuel-based electricity to carbon-free sources, the stronger the effect. Yet additional factors such as the Bitcoin market price, electricity prices, and mining hardware developments have to be considered when estimating the decarbonization effect that can be attributed to green mining incentives. Again, the climate benefit observed for the Bitcoin network might result in a waterbed effect and trigger higher emissions in other sectors which previously used the renewable energy sources now used by green miners.

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[3] Example: Considering total network emissions of 100 Mt CO_2 and a block reward of 9 BTC and a tx fee of 1 BTC (f=9/10; f-1=1/10). There are 100 coins and 100 tx. The GMI user holds 1 coin and executes 1 tx.
Scenario 1 (no GMI): Carbon footprint = 100 x (9/10 x 1/100 + 1/10 x 1/100) = 1
Scenario 2 (GMI with green miners i.e., g = 0): Carbon footprint = 100 x (9/9.99 x 1/100) = 0.901
In Scenario 2, total incentives decrease due to the missing 0.01 BTC tx free from the GMI transaction with almost zero tx fee. Still, total emissions are substantially lower in Scenario 2.

A second key benefit the GMI may bring besides emission reductions is transparency. The Bitcoin mining industry currently lacks disclosure and verification of climate claims. Introducing respective accreditation programs may help in gaining more transparency on the types and extend of energy sources used by Bitcoin miners.

Overall climate impact

To quantify the overall positive climate impact from emissions reductions brought by the GMI, we need to look at the additional clean energy resources deployed by green miners. Only such additional clean energy generation resources should be counted when calculating the overall climate benefit of the GMI. The GMI can be an effective tool, especially in cases where the green incentive triggers investment decisions in such clean resources.

Already today, there are some examples of crypto miners that have invested in renewable energy sources. Optimal sites for generating energy from renewable resources are often in remote regions with insufficient local demand, energy storage capacity, and transmission infrastructure. Two notable examples are a partnership of Tesla, Block, and Blockstream to set up a 3.5 MW solar-powered Bitcoin mine in Texas, and Aspen Creek's 30 MW off-grid mining facility.[13] However, linking such investment decisions to the GMI in the future will remain challenging as various other costs and revenues determine the respective business cases.

4. Conclusions & outlook

The GMI offers an effective tool to incentivize miners that already use clean energy sources and support others to switch from fossil to clean energy sources. For GMI users, the initiative yields immediate impact in corporate or individual GHG accounts and is an effective tool to reduce emissions that were previously hard to abate. The impact of the GMI to accelerate overall Bitcoin network decarbonization and global net climate benefit depends on additional parameters such as the adoption rate of the GMI, which future research may quantify once the GMI is fully launched.

It is noteworthy that the GMI may also bring climate and environmental impact beyond CO_2 emissions reduction. Incentivizing the usage and expansion of clean energy generation resources may also reduce negative externalities for air and water pollution, or biodiversity degradation. Furthermore, sustainability impacts beyond the climate and environment domain should be considered. The GMI, for instance, offers a channel to route transactions to trusted miners in jurisdictions that comply with broader corporate sustainability policies and codes of conduct.

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About CCRI
CCRI – Crypto Carbon Ratings Institute – is a research-driven company providing data on sustainability aspects of cryptocurrencies, blockchain and other technologies. The interdisciplinary team has built a multi-year research track record with a specific focus on cryptocurrencies and their sustainability impacts. CCRI uses the most up-to-date data sources as well as methods based on peer-reviewed studies published in renowned scientific journals. CCRI provides insights that help their clients to understand and manage crypto-related ESG exposure. CCRI works with a broad range of clients including institutional investors, exchanges, and blockchain networks. As the leading provider of sustainability data and indicators for crypto assets, CCRI has deep experience in helping clients to conduct crypto-related climate disclosures.

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