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Implausible projections overestimate near-term Bitcoin CO_2 emissions

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Bitcoin mining is an increasingly energy-intensive process[1–3] for which the future implications for energy use and CO_2 emissions remain poorly understood. This is in part because—like many IT systems—its computational efficiencies and service demands have been evolving rapidly. Scenario analyses that explore these implications can therefore fill pressing knowledge gaps, but they must be approached with care. History has shown that poorly constructed scenarios of future IT energy use (often a result of overly simplistic extrapolations of early rapid growth trends) can spread misinformation and drive ill-informed decisions[4–6]. Indeed, the utility of an energy demand scenario is proportional to its credibility, which is demonstrated through careful attention to technology characteristics and evolution, analytical rigour and transparency, and designing scenarios that align with plausible future outcomes.

While we believe that Mora et al. had the right motivations in developing Bitcoin CO_2 emissions scenarios[7], we respectfully argue that their scenarios lack such credibility. We arrived at our conclusion by replicating Mora and colleagues' methods in detail, which revealed key flaws in the design and execution of their analysis (as documented in the Supplementary Information). We describe the five most important issues below.

First, the use of transactions as the driver of future Bitcoin emissions is questionable, given the tenuous correlation between transactions and mining energy use. It is well established that energy use is driven by the computational difficulty of the blocks mined[1–3], whereas the number of transactions per block can evolve (for example, via SegWit)[8] with no direct effect on block mining difficulty. The authors themselves[7] calculate Bitcoin energy use and emissions in 2017 on the basis of block difficulty, not the number of transactions (Supplementary Equation (1)). Without explanation, the authors switch to transactions as the driver for projecting future emissions, undermining their methodological consistency and the integrity of their projections.

Second, all three Bitcoin adoption scenarios designed by Mora et al. represent sudden and improbable departures from historical trends in Bitcoin transactions; over the preceding five years annual growth ranged from 1.3× to 2.3× (Supplementary Figs. 3 and 4)[9]. Specifically, Mora et al. assume that Bitcoin transactions—which totalled 104 million in 2017, representing a mere 0.03% of global cashless transactions—would abruptly leap to 78 billion by 2019 in the fast scenario (a 750× increase in only 2 yr), to 11 billion by 2020 in the median scenario (a 108× increase) and to 8 billion by 2023 in the slow scenario (a 76× increase). All three adoption scenarios follow steep logarithmic growth trajectories thereafter, which are conspicuously inconsistent with historical trends (Supplementary Fig. 4) and mathematically can only lead to large near-term emissions increases. The authors base their scenarios on adoption rates of 40 arbitrarily selected technologies, the social utilities of which vary widely. The authors do not explain why such comparisons are valid, nor do they justify the plausibility of the very abrupt changes in Bitcoin transaction levels and growth trajectories that result from such comparisons.

Third, Mora et al. applied outdated values for mining rig efficiencies and electric power CO_2 intensities, which inflated their estimated 2017 Bitcoin energy use and CO_2 emissions values considerably. When estimating the direct electricity use of Bitcoin mining, the authors included in their selection pool many old and inefficient rigs that were no longer economically viable in 2017 (Supplementary Fig. 5). Furthermore, Mora et al. provided equal weighting when selecting a rig from their pool as the sole rig type to mine a block, thus over-representing slower, inefficient rigs and creating scenarios that require physically impossible rig counts. When we excluded unprofitable rigs in our replicated analysis, Mora and colleagues' model produced an estimate of 28 TWh in 2017 (Supplementary Fig. 6), which is one-quarter of their original estimate of 114 TWh. Furthermore, they applied 2014 CO_2 intensities (in $gCO_2\,kWh^{-1}$) to calculate 2017 emissions, ignoring non-negligible grid decarbonization improvements in the intervening years (Supplementary Fig. 7)[10], despite sufficient data being available at the time of their study for reasonable estimates of 2017 power mixes[11,12]. Applying more reasonable 2017 electricity use and CO_2 intensity values in their model produced an estimate of 15.7 $MtCO_2e$, far lower than their original estimate of 69 $MtCO_2e$.

Fourth, by analytical design, Mora et al. applied 2017 per-transaction energy use and CO_2 emissions values in all future years, multiplied by annual transactions (Supplementary Equation (2)). This decision effectively held both mining rig efficiency and grid CO_2 intensities constant for the next 100 yr (Supplementary Fig. 7). This unprecedented choice ignores the dynamic nature of mining rig and power grid technologies and violates the widely followed practice of accounting for technological change in forward-looking energy technology scenarios[10,11]. In acknowledging their static grid intensity assumption, they point to at least one reference containing credible grid intensity outlooks[10] but failed to make use of them. Estimating the future energy efficiency of mining is certainly more difficult, but the authors do not explain why they simply ignored this

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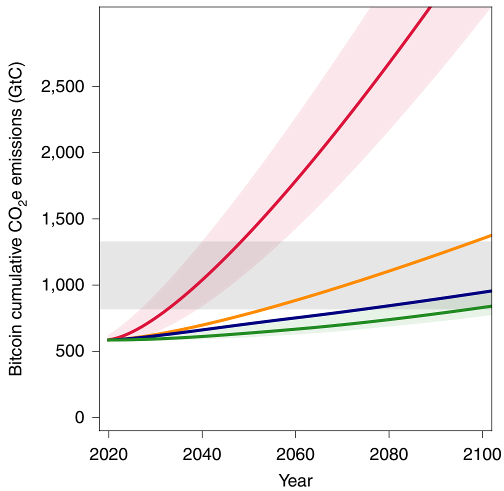

Fig. 1 | Comparison of Bitcoin CO_2 emissions projected by the Mora et al. model. Our replicated analysis (red) shows close agreement with the results of Mora et al. The replicated model's projections after first removing unprofitable rigs in the base year (median scenario only, orange), then after accounting for evolution of the electric power grid in mining locations (median scenario only, blue) and finally after correcting the errors in the adoption scenarios derived by Mora et al. (green) are also shown. The grey shaded area indicates the carbon emissions above which warming exceeds 2 °C, according to the Mora et al. analysis. The red and green shaded areas indicate the scenario ranges around the red and green median curves, respectively.

important scenario consideration, nor do they justify how assuming static mining efficiency for 100 yr—when mining rigs have evolved monthly[1]—can lead to any useful insights.

Fifth, in constructing their scenarios, Mora et al. committed key errors when analysing adoption rates within their 40-technology comparison pool[13]. Specifically, when replicating their analysis, we discovered that for many comparison technologies they misinterpreted their first available data point as the first year of actual technology usage. For example, the authors designate the first year of usage for electric power as 1908, at which point US household adoption had already climbed to 10% (Fig. 1b in ref. [7]). Yet Thomas Edison began commercially offering electric power to (far fewer) US households in Manhattan in 1882, a quarter-century earlier[14]. By omitting the initial low-adoption years of US commercial availability for numerous technologies, their scenarios were biased towards inaccurately steep near-term adoption trajectories in all three cases. When we replicated their analysis using more reasonable estimates of the first year of technology usage, their own methods produced slower adoption curves (Supplementary Fig. 8).

To assess how these last three analytical flaws affected Mora and colleagues' projections, we replicated their original scenario analysis (red curve in Fig. 1), and then applied reasonable adjustments in their model in a stepwise fashion. We first applied the 2017 per-transaction Bitcoin carbon intensity we obtained by excluding unprofitable rigs (orange curve, Fig. 1). We then used weighted-average grid intensities based on the mining locations assumed by the authors, but included grid intensity evolution on the basis of International Energy Agency outlooks that reflect current and announced national power policies in mining locations (Supplementary Fig 7; blue curve in Fig. 1). Finally, we applied our adjusted version of Mora and colleagues' adoption curves in all three scenarios (green curve, Fig. 1).

The results show that, had the authors avoided the errors we described above, their own study design would have yielded much different—and far less alarming—projections of future Bitcoin CO_2 emissions. That said, we find the study design itself sufficiently unsound (for example, use of transactions as a driver, comparisons to 40 arbitrary technologies, ignoring rig evolution) that such adjustments are not enough to salvage the authors' approach. We therefore argue that the scenarios used by Mora et al. are fundamentally flawed and should not be taken seriously by the public, researchers or policymakers.

Given the highly dynamic and unpredictable nature of Bitcoin markets and mining demand—for example, Bitcoin transactions and exchange values dropped steeply in 2018—developing credible scenarios of cryptocurrency emissions remains an important challenge for the research community. While Mora et al. probably had the right motivations, such scenarios must be approached with more rigour and greater analytical care if they are to be of use.

Data availability

The authors declare that all data supporting the findings of this study are available in the article, the Supplementary Information and at https://github.com/emasanet/Bitcoin-analysis.

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Author contributions

All authors contributed equally to the conception and design of this critique, and to the preparation and review of the manuscript. E.M., A.S., N.L. and H.V. led the analytical components.

Competing interests

The authors declare no competing interests.

Additional information

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