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Mora et al. reply

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REPLYING TO: N. Houy *Nature Climate Change* https://doi.org/10.1038/s41558-019-0533-6 (2019)
REPLYING TO: L. Dittmar & A. Praktiknjo *Nature Climate Change* https://doi.org/10.1038/s41558-019-0534-5 (2019)
REPLYING TO: E. Masanet et al. *Nature Climate Change* https://doi.org/10.1038/s41558-019-0535-4 (2019)

In a recent Comment[1], we used climate model projections to estimate the amount of CO_2 required to surpass 2 °C of global warming. We compared these emission requirements with the potential cumulative emissions of a scenario in which Bitcoin is adopted as a mainstream form of currency, following a rate of adoption shown by broadly adopted technologies and assuming that current conditions in Bitcoin mining remain constant. Between 231.4 and 744.8 GtC would push global warming across the 2 °C threshold, and we found that the lower estimate of emissions may be produced in a few decades if Bitcoin rapidly replaces cashless transactions under current conditions[1]. Several authors have cautioned our findings[2–4], but their criticisms arose primarily from their misunderstanding of what our study was intended to accomplish.

Scenarios are commonly used in multiple disciplines to assess the consequences of certain actions. For instance, a large body of climate change work is based mainly on three alternative scenarios of GHG emissions, ranging from a halt in human carbon emissions to 'business as usual' (these scenarios are commonly referred to as Representative Concentration Pathways 2.6, 4.5 and 8.5). These scenarios are not meant to predict the future, but rather they help identify the relative consequences, risks and opportunities among these choices. The use of scenarios in our paper did not differ from how scenarios are typically used in scientific research[5–9]. Our work clearly established a scenario in which Bitcoin was broadly adopted for cashless transactions (that is, it replaced credit and debit card transactions) under current conditions. We did not attempt to speculate on whether such a scenario will come to pass; instead, we assessed the consequences (in terms of CO_2 emissions) if it does become true, with all else being the same.

Houy[2] suggested that the assumption of constant conditions was inappropriate, and that if only the most energy efficient hardware was used, Bitcoin emissions would be lower. That is certainly possible but, unfortunately, this assumption is prone to large uncertainties because it is not known whether miners will immediately replace still-profitable machines with more efficient ones, which would require substantial up-front costs. As an example, there are now several sources of clean energy that will reduce emissions considerably (some may even pay for themselves in a few years), yet their uptake is still limited, largely due to their large up-front cost. This example highlights that although it makes sense to use more advanced and efficient technologies, these technologies are not always immediately or broadly adopted.

Dittmar and Praktiknjo[3] suggested that electricity demand and price and the inability of the Bitcoin network to handle many transactions will render the scenario of Bitcoin becoming mainstream unlikely. Under current conditions, we would tend to agree: as demonstrated in our Comment, the emissions of Bitcoin usage under that scenario may be substantial and, given the broad consequences of climate change[9], considerable regulations on Bitcoin growth may be put in place. We also agree with Dittmar and Praktiknjo[3] that a likely 'carrying capacity' for Bitcoin growth may be determined by the amount of available electricity. Around the world, several conflicts have already emerged surrounding the excessive use of electricity in Bitcoin operations[10]. However, the actual level or threshold of that carrying capacity is unknown, and further study could provide insights. For instance, future work may determine how much electricity countries would allocate to Bitcoin mining before reaching maximum generation levels, how much carbon would be emitted from that process and whether there would be substantial emissions even before electricity constraints are imposed on Bitcoin growth.

Dittmar and Praktiknjo also pointed out constraints on Bitcoin growth that are imposed by the price of electricity and the capacity for transactions in the Bitcoin network. These two options are likely within the realms of possibility, but there are important counterarguments to consider. First, the cost of electricity varies greatly by country, which offers a margin of latitude for miners to move operations either within a country or elsewhere in the world. Electricity produced by coal remains cheap in many places, especially where emission regulations are lacking. Second, the growth of transactions in the Bitcoin network has increased exponentially. As mentioned by Dittmar and Praktiknjo, past upgrades to the Bitcoin network allowed for an increase in the number of operations; it is not yet clear whether another increase could be prevented. It is also unclear whether increase in the number of mining rigs could increase Bitcoin transaction capacity. In short, there are several uncertainties related to the possibility that Bitcoin growth may be restricted by the price of electricity and network capacity.

Masanet et al.[4] suggested that our scenario lacks 'credibility' and pointed out several issues. First, they asserted that our analysis of projected carbon emissions was flawed because it was based on transactions rather than the hash rates of the blocks. Their assertion was a misinterpretation of our methods. The projected emissions in our paper were based on the hash rates of blocks and their transactions (using 2017 as reference); details are provided in the

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Methods section 'Amount of CO_2e produced by Bitcoin usage'[1]. Second, they asserted that the adoption rates of technologies used did not resemble the growth rates of Bitcoin usage. We preferred to avoid making predictions about the projected usage of Bitcoin; however, in the realm of historical examples, there were several cases where technologies were slowly adopted, but eventually broadly incorporated (several of these examples are described in ref. [1]). Again, we had no motivation to predict the success or failure of Bitcoin usage. Our study only recognizes that going mainstream is a possibility that needs to be considered. Third, our Methods section[1] indicated that we assigned currently available hardware for Bitcoin mining randomly. Restricting the analysis to just efficient hardware would have reduced our emissions. The extent to which various hardware options are used by different mining operations is not known. As mentioned earlier, more efficient, faster machines may indeed reduce emissions and result in more profitability; however, they are also more expensive, may require a large up-front cost and may be replacing machines that are probably still functional and marginally profitable. The extent to which miners make these decisions to upgrade hardware continuously is unknown; we therefore treated this variable as random. Fourth, we ignored likely improvements in efficiency and grid CO_2 intensities. In our Comment, we acknowledged this limitation and clearly indicated that we used CO_2 emissions values for electricity production at current levels, based on information in the World Energy Outlook 2017 report by the International Energy Agency[11] predicting that such values and sources of production will remain relatively stable for the next few decades for which extrapolations are well supported. Lastly, Masanet et al. stated that we introduced errors in the choices of the first year technologies began to be incorporated that led us to find faster rates of adoption. They demonstrated their point by collecting years of earlier adoptions and then fitted linear models to recalculate rates of adoption. One peculiarity in the incorporation rate of broadly adopted technologies is that they were highly nonlinear. Commonly, they start slowly (although in recent times they are faster), increased exponentially and then saturated to nearly full incorporation. With these types of trajectory, collecting early data and fitting linear models will therefore lead to slower rates. What Masanet et al. failed to realize is that we applied logarithmic functions to these trends, which adjusted to nonlinear trends and prevented the considerable effect of missing data that they highlighted.

Finally, both Houy and Masanet et al. made predictions about Bitcoin emissions that were based on economic assumptions, such as the cost of electricity and the percentage of revenue from Bitcoin mining that goes towards electricity. These assumptions have been used to predict Bitcoin carbon emissions in other studies[12,13], but it is recognized that they are prone to uncertainty. Electricity prices vary considerably among countries and even within the same country; inclusion of this uncertainty will therefore broaden the range of modelled carbon emission values. Likewise, the proportion of revenue generated by Bitcoin mining that goes towards paying for electricity is unknown and including the broad range of possible percentages will also add to the uncertainty of carbon emissions that are estimated by means of economic profitability.

Our Comment was not intended to predict the future of Bitcoin, but to assess the 'what if' possibility of Bitcoin becoming mainstream as the primary form of cashless currency, all else held constant. There is certainly room for improvement, but the highlighted limitations do not undermine the main point of our Comment: there is a considerable risk of increased carbon emissions if cryptocurrencies are incorporated as a cashless currency at the same or similar rates to other broadly adopted technologies.

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Competing interests

The authors declare no competing interests.

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