

The environmental impact of cryptocurrencies: a clarification for Wendl et al. (2023)

Abstract

The interest in the environmental impact of cryptocurrency mining is illustrated by the research report published by the US Whitehouse and the banning of Bitcoin mining in China in 2021. Wendl et al. (2023) took the opportunity to explore research within the area using a systematic literature review approach, with the aim of developing a broad but also unbiased way to consolidate a lot of research in the area. However, while not taking away from the work of the author, there are some serious issues associated with many sources that are drawn from. As a result, this paper aims to highlight some identified problems with Wendl et al., specifically sources used directly, the sources used by particular references that contribute to presented findings and the findings themselves. This work provides a critical review of a recently published piece, so that the model presented within the work can be revised to reflect current practice, rather than basing the model upon past research. This work presents a revision of the model presented by Wendl et al. (2023) of bitcoin mining as a critical practice for both stabilising electrical infrastructure that uses inconsistent renewable sources of electricity and incentivising its development. Within the conclusion the work provides some direction on how policy can be developed moving forward.

Keywords: Bitcoin Mining, Renewable Energy, Academic Rigour, Environmental Impact, Electricity Grid

1. Introduction

Cryptocurrencies have garnered considerable interest and attention since the genesis block of the original cryptocurrency, Bitcoin, was released on the 3rd of January 2009 (Nakamoto 2009). Whether in terms of dramatic rises in asset values (Cheah and Fry 2015) or illegal activities that are said to take place using them (Foley et al. 2019). Alternatively, as a result of the increase in value of the currency, opportunities have developed where elaborate ploys for accessing individuals' bitcoin or appealing to their greed via "get rich quick" scams present themselves as "the next bitcoin" (Byrne and Bartlett, 2023). As a consequence, there are many different angles that Bitcoin can be viewed from, with this particular piece focusing upon the environmental angle. From the original presentation of the Bitcoin network (Nakamoto 2008), the means of linking the digital currency with the real world to issue new coins has been the foundation of some of the most strongly held opinions and has garnered most attention of wider public bodies. Quite simply, Bitcoin requires the expenditure of electrical energy, through a process known as mining (more precisely hashing), to assign new transactions to the blockchain, which is rewarded by the issuance of new coins (Nakamoto 2008). Likely as a result of the physical nature of mining infrastructure, the processes that are used to generate the electrical energy and the measurable amount of energy used across the network, critics have objective data on which to base their arguments on what is or is not an appropriate use of electricity (Namabiampurath, 2023).

In 2022, the Whitehouse commissioned a report into the implications of crypto-assets (OSTP 2022), with a strong emphasis on the higher standard of academia and rigor. Academic, systematic and rigorous research provides a means to explore the topic further, so helps either confirm or reject previously held views. In theory, this process would allow the government

held position of crypto assets to move away from more widely held beliefs, and support a united position to move forward from. However, in his review of the report, while Carter (2022) was able to find both, logical views he also found a number of the studies that were drawn from that were a combination of personal blogs, non-peer-reviewed journal articles, reports funded by biased sources and at worse “junk science”. Wendl et al. (2023) represented an opportunity to explore this issue in depth, using a systematic literature methodology (Tranfield et al. 2003) to identify and review 1237 papers covering topics such as cryptocurrency, environment, energy and “proof of work” to name a few. Unfortunately, when reading Wendl et al. (2023), disappointingly, they drew extensively from the same works as those identified by Carter (2022), which included that of De Vries and the Digiconomist (De Vries’s personal website). Given Wendl et al. (2023) is an academic literature review, one would hope that a single cited author would not affect the findings of the paper as a whole, however, a number of the sections rely heavily on the work of De Vries. One would also hope that as a peer-reviewed journal, attention would be given to identifying those non-peer reviewed sources, and requesting revisions before work was accepted.

The following section provides a brief overview of some of the issues with sources drawn from by Wendl et al. (2023), before presenting works drawn from that take a more positive perspective on the role of Bitcoin mining. This section moves onto to drawing from publicly available data from experts within the bitcoin domain, supporting by related data to develop 4 illustrations of how bitcoin mining can operate within an energy grid. From this position, an adapted version of the figure summarizing the work of Wendl et al. (2023) is presented, to illustrate the limitation with the previous version and the positive, rather than negative impact bitcoin mining can have on the environment. The work also provides a perspective on the identified limitations of academic research within the field, with suggestions for its improvement.

2. Standing of the Shoulders of Giants?

Alex De Vries established his website in 2014, with the aim of exposing the unintended consequences of digital trends, although quickly, the focus of the site emerged as “the gigantic environmental impact that the cryptocurrency Bitcoin had” (1). From a background in consultancy with PwC, as a data scientist working for the Netherland’s national bank and more recently becoming a PhD candidate at the Vrije Universiteit Amsterdam, there appears a strong foundation for systematic and robust research. However, from a cursory glance of the website, questions about the data being reported begin to be raised, not least in terms of presenting the carbon emissions associated with a “Single Bitcoin Transaction Footprint”. While confirming and processing transactions is a central part of the Bitcoin network, new blocks can and will be produced that contained zero transactions. This was the case when the network was first online, when Satoshi Nakamoto was producing blocks but had no one to send Bitcoin to and can also take place today (Dicki 2023). As a result of the energy Satoshi was expending, which was non-zero as way the energy used this year, as there were zero transactions being processed, the energy per transaction was effectively infinite. As this calculation makes no sense, it can be accepted that while the nodes confirming transactions do consumer energy and it is much less than the amount associated with the mining aspect of the network, this figure is not associated with transactions. As a result, the figure of 731.58kWh of energy and 408.04kgCO² per transaction (1) is at best highly misleading and a worse, the deliberate presentation of false data.

No.	Authors	Date	Title	Source	Resource type	Comment
1	De Vries, A.	2014-2023	The Digiconomist	digiconomist.net	Personal Website	Energy use "per transaction" and Bitcoin mining's need for constant energy
2	De Vries, A.	2018	Bitcoin's Growing Energy Problem	Joule	Commentary	Balances broadly accepted works, providing an outline of what is happening, but presents data without sources (table 2), uses "Bitcoin Energy Consumption Index" from the Digiconomist
3	De Vries, A.	2019	Renewable Energy will not solve Bitcoin's sustainability problem	Joule	Commentary	links to Digiconomist. Self cites De Vries (2018) to estimate computational power and mining rewards, using direct quote for the industry moving to the most cost efficient machines
4	De Vries, A.	2020	Bitcoin's energy consumption is underestimated: a market dynamics approach	Energy Res. Social Sci.	Research Article	Self cites De Vries (2018) and De Vries (2019) and cites Digiconomist directly, but is unable to provide a breakdown of some of the data presented.
5	De Vries, A.	2021	Bitcoin boom: what rising prices mean for the network's energy consumption	Joule	Commentary	Vries (2019) related to short life of miners. De Vries (2020) in terms of destabilised local grids, which the work did not mention.
6	De Vries, A., Stroll, C.,	2021	Bitcoin's growing e-waste problem	Resource, Conservation & Recycling	Research Article	Cites Digiconomist and 4 self authors pieces, including De Vries (2020), which references a performance adjustment factor, that is not mentioned within the original work.
7	De Vries, A., Gellersdörfer, U., Klaaßen, L., Stroll, C.	2022	Revisiting Bitcoin's carbon footprint	Joule	Commentary	Draws from Digiconomist data used without assigning, inaccessible "data sheet" and misrepresented issue of "stranded energy"

Table 1: Summary of De Vries articles (Deliberately not included in reference list).

A second statement that is highly questionable is in relation to the use of renewable energy by Bitcoin miners, is that “Bitcoin miners have a constant energy requirement” (1). Given that the proof of work process is probabilistic, on average, it is always approximately 10 minutes until the next block is mined, meaning that miners do not forfeit anything if they turn off their machines. The result of this is that Bitcoin (or more generally proof of work) miners, can turn on or off their machines at short notice, meaning they can make use of sources of energy that would otherwise be wasted or release energy if demand were to spike (Carter 2021b).

Overall, the sources of the data being drawn from, whether in terms of the energy consumption, distribution across countries or the level of E-waste is not immediately apparent and given the quite obvious errors (mis-truths), this raises significant doubts on their validity. This source is cited 6 times by Wendl et al. (2023).

However, personally funded websites can present whatever the owner wants to present, be it factual, counter factual or even fantasy, which is why within academia, attention is given to the use of journal articles, rather than websites within literature reviews. This means that rather than the data on the Digiconomist being wholly at fault, responsibility must lie with those who choose the use such a resource in their own work (and reviewers willing to accept the use of such sources). As a result, the direct use of sources from the Digiconomist need to be used with significant context, suggesting the direct citations of the source by Wendl et al. (2023) need to be questioned. However, De Vries has been able to solidify the foundation of his work with the publication of Journal articles, presented under the research tab of the Digiconomist. Of the works cited within Wendl et al. (2023), 4 of these were published in the journal “Joule”. Carter (2022) stated the journal was not peer reviewed. While specific details of the review process are not given, Joule does appear to adopt a Peer view process, “promoting the rigor and high quality of scientific research”. However, each of the cited pieces published in Joules are “commentaries” rather than articles, so are not actually subjected to the review process, so cannot be considered of the same academic rigour as other works in this journal. The works thus have an appearance or “vener” of academic rigour, masking the potential motivations and biases of the author.

While not attempting to review the 6 articles in depth, a cursory scan can quickly identify both questionable sources and practices of De Vries. The first piece, De Vries (2), builds a

foundation for the work upon widely accepted sources, with attention moving onto energy and equipment use, which use figures and indexes taken from the Digiconomist. The second piece, De Vries (3), using a more subtle and concerning approach of using the bitcoinenergyconsumption.com source to predict future energy consumption. Interestingly, this URL redirects the user to Digiconomist, so hiding the true source of the data. The work also directly quotes De Vries (2) in terms of estimates of computation and mining rewards, in terms of the age of the machines being the primary driver of mining operator profitability, which overlooks the energy cost as a critical driver of profitability (K33, 2022, Duggan and Powell 2022). Interestingly, the third piece, De Vries (4) is not a “commentary” piece and published within a peer reviewed journal (Energy Research and Social Science). The work draws from both De Vries (2) and De Vries (3), and citing Digiconomist directly. Interestingly, the work draws from the Bitcoin Energy Consumption Index, a measure developed by the Digiconomist, but says “further breakdown is unavailable”. Given De Vries (1) is the developer of this index, if they are unable to breakdown this index further, the question is raised of whether anyone can further breakdown this measure?

The fourth piece, De Vries (5), does not cite the Digiconomist directly, but draws from the first two commentaries in terms of cost estimates for mining (2) and the short life of mining equipment (3). Of particular interest within this work is the use of De Vries (4) in terms of how Bitcoin Mining destabilised the Quebec grid, although this was not mentioned within this particular work, only the increase in rates charged to miners and questions for additional power that “*couldn't be taken seriously*” (4, p.2) by regulators, due to their size. While there was potential for bitcoin mining to change the structure of the Grid in Quebec, nothing is mentioned about destabilisation, inferring an error in self-citation. The fifth piece, De Vries and Stoll (6), was published in Resources, Conservation & Recycling, that underwent a single anonymised review, so associated with higher academic rigour than the commentary pieces. Interestingly, the co-author is associated with the highly prestigious Massachusetts Institute of Technology (MIT), although only in the capacity of a visiting student, rather than a member of staff. The work directly draws from the data of Digiconomist, figures for energy cost per transaction and earnings per miner from De Vries (3) and refers to De Vries (4) in relation to an “adjustment factor”, which is a 5% increase to an estimate related to miners using more than advertised power values (no source given for this). Finally De Vries et al. (5) is cited in relation to power usage estimates based on bitcoin price. This final piece was not referenced by Wendl et al. (2023), although it too is another non-peer-reviews “commentary”.

The final piece cited by Wendl et al. (2023), De Vries et al. (7), introduces 2 addition co-authors along with Stoll, interestingly the co-author Klaaßen was also a visiting student at MIT (consistent with Stoll), with all three co-authors being associated with the Technical University of Munich, as a research associate (Gallersdörfer), PhD Student (Klaaßen) and research affiliate (Stoll). The sources drawn from show the co-authors have further Bitcoin related publications, not limited to commentaries. Interestingly, this piece only cited de Vries and Stoll (6), but appears to use data from Digiconomist (1) without identifying the data as such, instead linking a data sheet (that is not accessible). Refreshingly, the work covers the issue of stranded fossil assets (to be discussed later) but interprets this as bitcoin mining leading to the recommissioning of coal power stations. While mentioning the application within gas flare mining, this is only stated as a carbon neutral approach compared to gas

flaring alone. However, this does not highlight the economic incentive of adding the revenue generation of bitcoin mining to an otherwise costly practice, the work also wholly overlooks the ability of bitcoin mining to incentivise otherwise wasted and highly environmentally damaging emissions of methane from such sites (EDF 2023). For example, companies such as Vespene (2023) illustrate how bitcoin miners are able to make use of otherwise dangerous and stranded sources of energy to create economic value through bitcoin mining, which is totally overlooked by De Vries and colleagues.

As a result of the limitations identified of the above work, this raises questions related to the impact of this work on the findings of Wendl et al. (2023). Not only was the Digiconomist (6) cited directly 6 times, of the 7 themes identified by Wendl et al. (2023) that made up their framework, all are influenced by the works of De Vries and colleagues, without considering the cited works, that themselves may have drawn from the work of De Vries (see below). Of the topics covered by Wendl et al. (2023), the section on electronic waste was of particular concern with the majority of sources drawn from being those of De Vries. While Wendl et al. (2023) draws from an impressive 1237 items, only 44 works were actually included within the literature review, with De Vries making up over 13% of the sample. Also of note, within the very useful table within the appendix of the source articles, no mention was given that 4 of De Vries's publications were actually non-peer reviewed "commentaries".

3. Further Problematic Sources

Although the work of De Vries has been given specific attention as a result of the number of citations by Wendl et al. (2023), due to his acknowledgement by Carter (2022), and for brevity, unfortunately, all sources used by Wendl et al. (2023) cannot be verified. However, two additional sources were identified, as a result of the scale of the figures present appearing large, even when compared to figures presented by De Vries and the Digiconomist. Firstly, within the section on carbon footprint of proof of work mining, a very wide range of figures was given, from 3 megatons of CO₂ (Krause and Tolaymat 2018) to the figure of 29.6 Megatons of CO₂, the upper bound presented by de Vries (3) for emission in 2018. However, the largest figure presented was over twice this, at up to 69 Megatons of CO₂ presented by McCook (2018). Given the questions raised with the figures presented within De Vries (3), such an increase and difference warrant further investigation into this source.

Rather than a peer reviewed journal article, this McCook (2018) was published on academia.edu, a website used for collating published sources of academic researchers, with the origins of the work not made clear. Interestingly, the work is an updated version of a piece originally published in 2015 to estimate the costs associated with mining a single Bitcoin. However, points need to be raised, both in terms of the figures presented by Wendl et al. (2023), and the credibility of the source. McCook (2018) stated that the Bitcoin network "exhales 63 million tons of CO₂" (p.ii), as opposed to the stated 69 (Wendl et al. (2023, p.5). It is then not stated by Wendl et al. (2023) that this figure includes "the impact of the manufacture of ASICs, which represented over 50% of all emissions generated" (p.ii). Although the academic standard of the work can be questioned with origins of the source unknown, as an interesting aside, the author acknowledged Klaaßen (see source 7 table 1), for their review of the methodology and calculations. Notwithstanding the unknown origins and aims of the original publication, the inaccurate presentation of the figure, and not providing

necessary information about the figure, raises further questions about the rigour and accuracy of Wendl et al.'s (2023) work.

The second piece of note was Truby et al. (2022), made (in)famous as a result of news associated with the publication when it was originally released (Shahadi 2022). Again, for brevity, the details of the paper will not be discussed in full, although there were a number of issues identified, firstly, the paper was related to the impact of digital art (Non-Fungible Tokens) on the environment, meaning the topic of the paper was not actually related to Bitcoin. Secondly, the figure used to calculate the number of unnecessary deaths was taken from Bressler's (2021) work, which interestingly was not included in the reference list of Truby et al. (2022), but rather included as a footnote. Bressler (2021) explored the relationship between excess deaths and lifetime CO₂ emissions in a variety of countries but did not appear to consider other factors that may contribute to life expectancy (such as obesity for example). They found that 4434 additional tons of CO₂ emissions would result in one excess death. Given many health and life expectancy related benefits from increasing use of hydrocarbons (Epstein 2022), without considering other factors for excess deaths this figure appears rather hollow, if not meaningless. Thirdly, to calculate the total number of excess deaths attributable to Bitcoin mining, Truby et al. (2022) used the figure of 4434 tons to calculate the number of deaths, by dividing the emissions of the Bitcoin network by 4434. The figure for total CO₂ emissions (along with a number of footnote references) were taken from the Digiconomist of 84.2 mtCO₂ per year. As a result, Truby et al. (2022) present a figure on a topic they are not actually writing about, using data from a questionable source, but choose to include this figure within the abstract of their work, a potentially questionable practice to increase engagement with the work.

4. A more positive angle on Bitcoin Mining

Given that Wendl et al. (2023) applied a systematic literature review methodology to potentially remove bias from the process of selecting works for inclusion, even though 1237 pieces of work were identified, only 50 relevant papers were identified (p.2). While information on the exclusion criteria was provided in terms of focusing only on proof of work or proof of stake algorithms with a focus on the environment, some potentially relevant papers may have been excluded. Withstanding this potential limitation, Wendl et al. (2023) were able to identify a few papers, that were against broader opinions that proof of work crypto mining had a negative impact on the environment. Firstly, it must be noted that the process of proof of work crypto mining does not produce any carbon emissions, given that it is powered by electricity alone, so it is bad for the environment (Wang et al. 2022), in the same way that electric cars are. Although, given that electric cars replace the direct emissions from internal combustion engines, it is less obvious whether the use of the bitcoin network electricity usage replaces existing sources of carbon dioxide emission. Given bitcoin functions as money, it could be considered as a replacement to parts of the banking system, which given the UK Finance sector, alone, produces 805 mtCO₂ in 2019 in the UK alone (WWF 2023), transitioning away from the major polluter to bitcoin could be net positive for the environment.

While the systematic methodology of Wendl et al. (2023) ensured all potential sources were considered, the attention given to more positive perspectives on bitcoin mining within power infrastructure was rather limited. Kristonfek (2020) and Apatova et al. (2020) suggested

bitcoin mining could help balance power grids and stabilise intermittent energy sources. Disappointingly, Kristonfek (2020) was cited once and provided only a single sentence is relationship to this potentially important contribution of proof of work mining. Apatova et al. (2020) was used elsewhere in Wendl et al. (2023), but primarily in relation to the negative impact of cryptocurrency mining on the environment. Given that both wind and solar sources are by their very nature dependent on the weather, electricity grids made up of these sources are inherently intermittent (and unreliable). As a result, having a customer willing to pay for energy that was not otherwise needed (on a sunny, windy day) or shut off when demand was higher (when it is cold), is likely to be very important (which bitcoin miners can do). However, this characteristic of proof of working mining was not mentioned with wind and solar sources of energy were only mentioned once (p.7.).

Wang et al. (2022) was used to provide some interesting, but ultimately logical and sensible points, stating that it was the energy source, rather than the cryptocurrency itself that negatively impacted the environment, which could be enforced by policy change. Unfortunately, this and Kristonfek's (2020) views were later offset by work with conflicting arguments. Atkins et al. (2021) and Ullrich et al. (2018) were used to evidence how bitcoin mining can be a threat to power grids, by adding load to traditional systems, unable to cope with increased demands or adapt when miners were turned on or off. This is an interesting perspective, particularly if a lot of bitcoin miners arrive in a specific region without infrastructure changes. Empirical evidence from Texas in 2021 demonstrates that having a significant number of Bitcoin miners in a region with appropriate power agreements helps release power by shutting off operations and providing homes with the necessary power (Gkritsi 2022). Rather than taking this perspective on the role of bitcoin mining, Wendl et al. (2023) took the "risk of blackouts" perspective. As a result, their model focused upon how energy consumption contributed to blackout that could have a negative impact on environmental related social aspects. The model also omitted the potential role of renewable energy within the framework, that if the aim was to reduce environmental impact was likely to be important.

As mentioned previously, bitcoin mining can play an important role in balancing electrical grid, which can be particularly important if there is a portion of generation is from renewables, by adjusting the miners to balance against variable generation. Tory Cross (2022) provided a clearly reasoned extension of this argument for building new renewable energy generation infrastructure. Rather than simply building power generation infrastructure and the associated transmission together, Cross (2022) suggested that before connection to a grid, through colocation of mining equipment it was possible for infrastructure to start generating income immediately. As previously mentioned, by maintaining the bitcoin mining with the renewable generation, revenue could be generated from infrastructure, even when there wasn't demand for the power through bitcoin mining. Cross (2022) suggested that the impact of this was more profitable energy generation, shorter periods of amortization and a more consistent source of electricity for the wider grid. Without giving attention to both the development of renewable energy along side variable loads within variable loads about to balance energy systems, significant risks can be present within an energy grid (Nwanekezie et al. 2022).

This characteristic of bitcoin mining not requiring physical infrastructure to connect to the wider grid also provides additional opportunities not covered by Wendl et al. (2023).

Reflecting onto the work on De Vries (specifically source 6), there are opportunities for bitcoin miners to make use of otherwise stranded fossil fuels, for example, gas emissions from oil wells, that may not be large enough to justify connection to wider gas infrastructure. However, unlike De Vries's view on this form of energy being carbon neutral, when methane is emitted directly into the environment, it is 80 times more damaging to the environment when compared to carbon dioxide (EDF 2023). As a result, reducing methane emission is considered a crucial opportunity to reduce an emission that contributes 25% to today's global warming emissions. The locations of these emissions is distributed across the global, whether it is oil wells, refuse sites, agriculture or parts of nature, they are seldom located where energy is needed. To reduce the extent of these emissions, operators can install gas flaring infrastructure to burn of the gas, with is both expensive to install, provides no revenue and may not result in complete combustion. In comparison, Wright (2022) outlined how installing electrical generation equipment at such sites could both more efficiently use methane within a generator while simultaneously providing a financial return to offset the cost of the equipment and provide an income of otherwise wasted gas. Given Wendl et al. (2023) was looking at the environmental impact of cryptocurrency mining, overlooking an avenue with such a dramatic contribution is a significant omission.

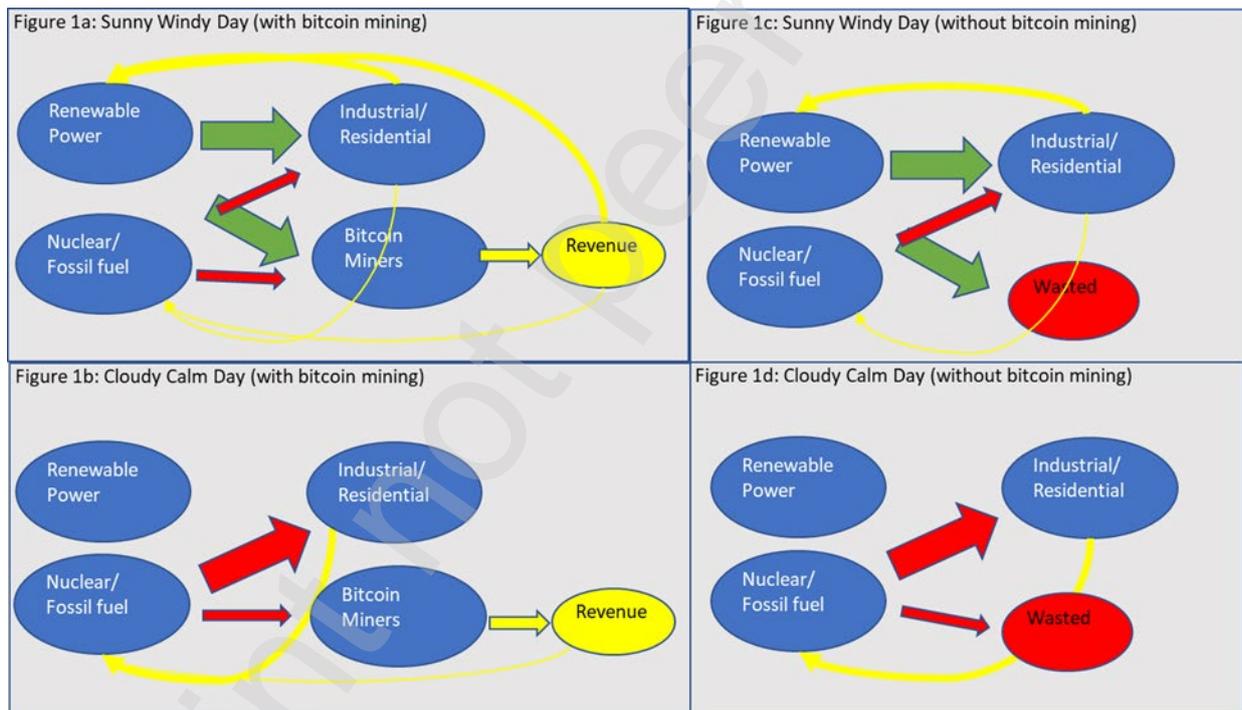


Figure 1: Renewable, Traditional and Bitcoin Mining power grid scenarios

Although overly simplistic, the above diagrams provides an idea of how power generation can work when there is a combination of renewable energy with bitcoin mining, compared to renewable energy generation (with traditional sources alone). In the situation where it is both sunny and windy, as the nature of renewables requires overbuilding of capacity so demand can be met for more of the time (e.g. 70% solar power generation at 10am meets 100% of the demand), there will be over production at certain times. This is illustrated when transmission capacity is not sufficient to get electricity from areas where there is a lot of wind to areas that use a lot of electricity (Lempriere 2022). This both results in the loss of electricity wind farms can generate but can also incur costs, where the owners of wind farms are paid to stop

production (over £500 million in 2021). While, theoretically, this overproduction could be stored in batteries, battery technology is currently not capable of storing this level of production for longer periods of time. As a result, unless there is a demand that can be turned on (or up) when there is excess power, it is likely this extra energy will be wasted (or priced negatively as in the case of Texas (Gross, 2015)). In this situation it becomes very profitable for bitcoin miners to connect their equipment to the system to effectively get paid to use the electricity, while also powering down traditional sources of electricity.

In times where there is less production from renewable sources, the mining equipment can be turned off (or powered down), reducing the demand for traditional sources of electricity. Importantly, given that bitcoin miners are made up of many individual machines, they do not only act as a switch for whether or not there is excessive wind or sun, but can provide easily and accurately variable electrical loads. As a result of this, bitcoin mining is not only of use within grids that have renewable energy sources but can also be used to balance loads of traditional power generation sources with demand that can vary quickly. Compared to the ease and speed that mining equipment can be turned on or off, coal, gas and particularly nuclear power stations can be quite difficult to change their level of production. By adding bitcoin mining capacity between power generation and the power grid, traditional power stations can more effectively match demand, while simultaneously adding a revenue source, so improving the economics of these plants (MacLeod, 2022). In addition to the ability of balancing variable power generation and generating revenue for the power companies, bitcoin mining also increases revenue in the wider system, by adding high skilled jobs into communities that may have power infrastructure, but where industries that originally needed the power have now left (Sudock 2022). Bitcoin mining can also provide a critical addition to the establishment of new grids within developing countries, where demand may grow over time, creating a mismatch that can otherwise make traditional energy projects unviable. Both Lei et al. (2019) and Herman & Long (2023) illustrate how important this can be in the development of new, renewable energy infrastructure across Africa. Without the necessary financial incentives to promote private sector initiatives, countries can have great difficulty in developing power infrastructure, even if they receive financial assistance (Li et al. 2022). Su et al. (2023) demonstrated the significant contribution financial incentives were able to make to the development of green technologies, further highlighting the need to align energy and renewable targets, with financial incentives.

In addition to the functional aspect of bitcoin mining's ability to balance grids, there are two additional "wastes" that are mentioned by Wendl et al. (2023), one to a lesser extent than the other. Firstly, the primary focus of bitcoin mining equipment is to hash the algorithm in order to find a valid block necessary for winning the block reward (Nakamoto 2009). The result of this process is the bitcoin miners take in electrical energy and then emit heat energy as a result of the function of the application specific integrated circuits (ASICs). Interestingly, the only reference to this by Wendl et al. (2023, p.3) was in terms of the additional electrical waste that was created by the need for bitcoin miner to be cooled. From certain perspectives, bitcoin miners can be reviewed as electrical resistance heaters with fans to distribute the heat. To refer again to Namabiampurath (2023), this function of a bitcoin miner would suggest the need to tax the electricity used for one type of electric heater differently to another, simply because one type of heater does something in addition to heating. Importantly, this output of bitcoin mining does not need to be wasted, which was also not mentioned by Wendl et al.

(2023), with many examples of the exhaust gas being used as a source of heat for domestic homes or industry (Sarker 2022). In relation figure 1a and 1b, this may result in additional revenue streams resulting from selling the heat from the bitcoin miners.

Secondly, although not necessarily a positive angle, more attention was given to the electronic waste resulting from the use, consumption, and disposal of the bitcoin mining equipment, due to ASICs wearing out or being replaced by more efficient machines. In this section, Wendl et al. (2023) draws from the work of De Vries (3,5,6), highlighting figures related to the amount of electronic waste produced per transaction, which as stated previously, makes little sense. While drawing from a range of sources, Wendl et al. (2023) suggests that because miners need to use the newest equipment to remain profitable, equipment is obsolete within 18 months (p.3). Interestingly, no mention was given to the other factors affecting miner profitability, such as the cost of power which is a key determinant of profitability (Duggan and Powell 2022). The profitability of miners is also affected by the price of mining equipment, that itself can be affected by the price of bitcoin, meaning there were many issues to consider, not only the need to continually acquire new equipment. In addition to this, compared to the stated 18-month life of mining equipment, industrial sources suggest that equipment can last between 3 and 5 years (Compass 2023), with the potential to repurpose older, less efficient equipment to function primarily as heaters, but with a very low hashing output. Given that there are over 2 million deaths a year that result from Indoor woodburning stoves (Miller 2011), more bitcoin miners in the world could actually have a significant positive impact on this very concerning metric. Moving away from woodburning stoves can also have a significant positive environmental impact (Nautiyal & Kaechele 2008)

In bringing Wendl et al. (2023) together, figure 3 provided an interesting summary and overview of the issues that were identified within their literature review, with appropriate regulation being able to reduce carbon emissions by reducing the amount of bitcoin mining, energy consumption and e-waste. However, 7 of the 11 sources used to justify their model have been critically reviewed/questioned/ refuted in this paper, thus highlighting significant limitations of the validity of this model. Of those not covered Huynh et al. (2022) related price to energy usage (which is dependent on the source of energy), Goodkind et al. (2020) linked mining to environmental damage, Köhler and Pizzol (2019) stated carbon emissions increase with energy use and Shanaev et al. (2020) state that regulation can affect the price of bitcoin. While each of these sources provide logical (but not necessarily insightful) opinions, in each case, their environmental impact is dependent on the energy source, meaning the presence of each relationship is not necessarily negative. In order to provide, in the author's view, a more representative framework of the role of bitcoin mining within the environment, Wendl et al.'s (2023) model has been adapted to reflect the findings of this paper (Figure 2). Each of the elements of the original model remain, with the topics of each adapted to reflect the more positive (optimistic), energy abundant scenario, that is based on evidence related to current practice rather than misinformed sources used by Wendl et al. (2023), some of which were not peer reviewed and others presenting wildly inaccurate figures (e.g. Truby et al. 2022).

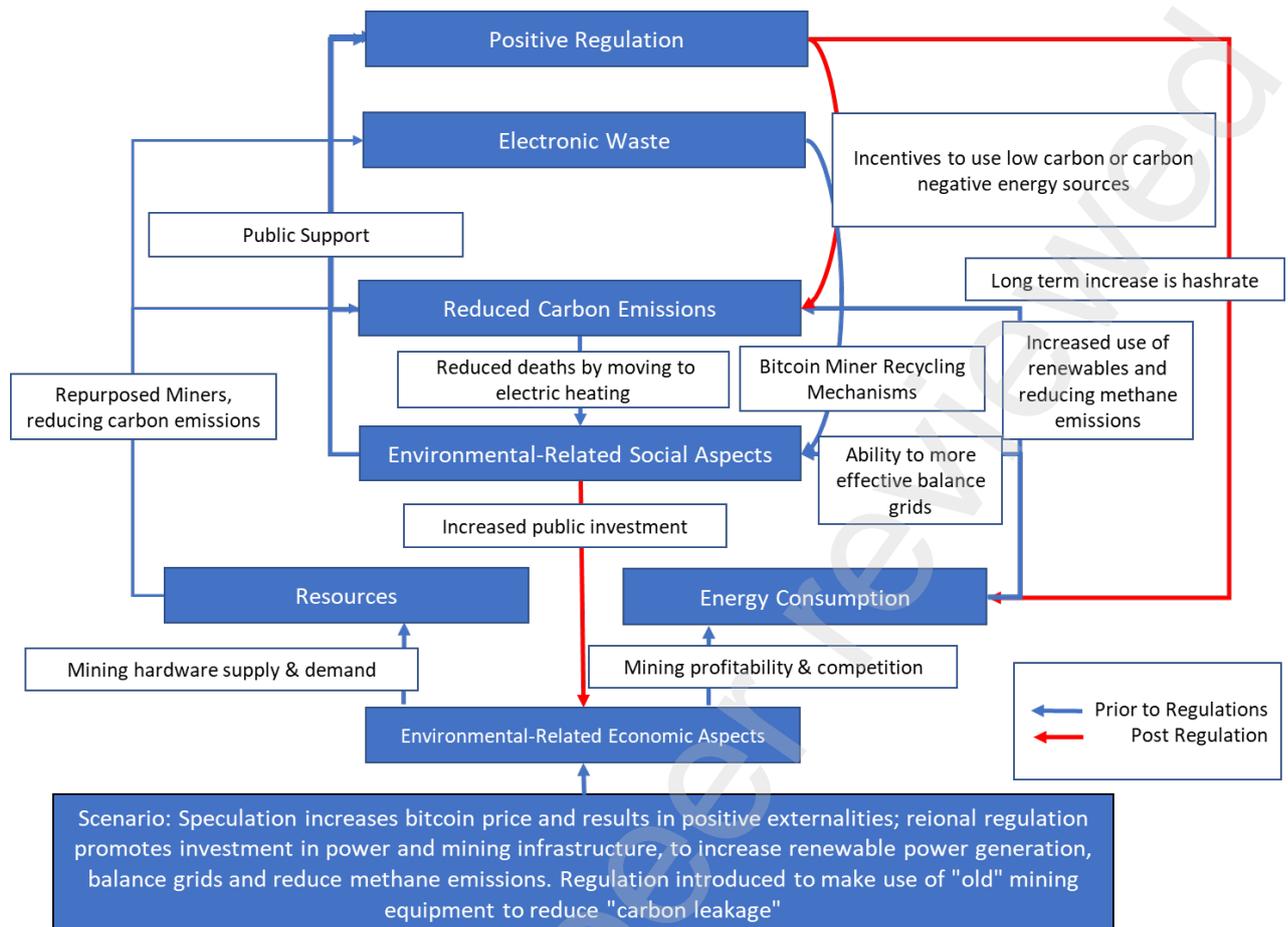


Figure 2: Scenario – Environmental externalities and interaction of seven environmental related aspects of Bitcoin Mining (Adapted from Wendl et al. 2023)

5. Conclusion and Policy Implications

Bitcoin is undoubtedly an important topic, that has considerable social, economic and environmental implications, with the potential to influence the lives of millions, if not billions of people around the world, as censorship resistant, undebaseable money (Ammous 2018). However, as stated in the introduction, news reports at times “catastrophise” the impact bitcoin is having on people’s lives, their finances, and the environment at large. For example, the New York Times (Dance 2023) felt it necessary to doctor images within a recent article on bitcoin mining, to make the scene look more polluted (Morris 2023). As a result, it is essential that rigorous, systematic and scientific research is undertaken, with the aim of holding a critical eye up to these widely held assumptions (Matthews 2023). Unfortunately, Wendl et al. (2023) shows that academia is not immune from the effect of non-academic sources and poor academic practice, that aims to present particular viewpoints under the guise of “rigor and high-quality scientific research” (Carter 2022). Interestingly, the critiques presented earlier show how this has been possible, by building a perceived foundation upon self-citation, that both misdirect the reader in terms of the sources they are drawing (3), or simply do not provide the data sources that are used (7). In their defence, Wendl et al. (2023) acknowledge the questions that have been raised in relation to the data presented by the Digiconomist (p.4), but these concerns were not applied to the sources they, themselves drew from.

Literature reviews are a critical part of academic research, enabling the reader to quickly, and efficiently, build awareness of large bodies of research, highlighting the importance of carefully selecting sources that are being drawn from (Tranfield et al. 2003, Matthews and Marzec 2012). Scientific research should also aim to remove bias, which this paper has done, by giving space and attention to ideas related to the positive impact of proof of work cryptocurrency mining, that were presented within figure 1 and 2. Unfortunately, a cursory scan by a time pressured academic of the “peer-reviewed” Wendl et al. (2023) may develop opinions associated with the significant environmental harm proof of work cryptocurrency mining can cause, when the academic rigour of many sources are highly questionable. Further work is needed that reviews literature on the scale of Wendl et al. (2023), that questions the sources drawn from, but also explores the sources of each source. Without such work, progress within the field of the environmental impact of cryptocurrency mining will not provide those new to the field, and those from outside the field (policy makers and journalists for example) the rigorous, academic and scientific foundation the topic deserves.

This critical review of Wendl et al. (2023) and bitcoin mining research more generally, combined with the exploration of the role of grid balancing in the previous section highlights a further problem with literature reviews in general. While providing a foundation of, preferably, strong academic rigour, such rigour comes at the expense of timeliness, with each of the sources hopefully, having undergone the peer review process, following the data collection and writing period. Therefore, while Wendl et al. (2023) is a very recent publication, drawing from many recent sources, much of the data and practices reported on are likely to be 2, if not more years old. Interestingly, over 100 literature reviews have been conducted on Bitcoin (appearing in title, abstract or keywords using scopus.com, up to the end of 2022), that while covering a range of topics from finance, “blockchain” and criminal use, amongst other topics, are each looking backwards. Given bitcoin has only been around since 2009, with much of that time as a little-known topic of ‘cypherpunks’, looking backwards can provide biased perspectives. For example, Foley et al. (2019) rigorously explored those using bitcoin, by looking back to early periods of bitcoin’s use. Given that many of the places that accepted bitcoin at this time were illicit (for example the Silk Road (Department of Justice 2022)), a portion of users during this period were involved in illegal purchases. By focusing upon this time-period, a headline figure of “46% of bitcoin transaction” (Foley et al. 2019, p.1798) were associated with illegal activities, which, in a similar way to Truby et al.’s (2022) work, was included within the abstract, to get the attention of time pressured academics, scanning abstracts. However, this figure is likely to be very different to how bitcoin is used today, particularly given that it has been national currency since 2021 (PWC 2023).

From the same angle of the time delay of sources literature reviews can draw from, this creates particular issues with the second focus of Wendl et al.’s (2023) review, the “proof of stake” cryptocurrency consensus mechanisms. In September 2022, the second largest blockchain (by market capitalisation) (Ethereum) transitioned from a “proof of work” to a “proof of stake” consensus mechanism (Ethereum 2023). One of the main reasons for this was to reduce energy consumption but also to support technical developments within the network that promote adoption. Interestingly, due to the recency of this development, very little research has been conducted on the actual environmental impact of proof of stake practices, with the literature referenced in this section presenting the benefits of this

approach, supported by the works of, amongst others, De Vries (3 & 6) and Truby et al. (2022). The result of this are recommendations that are, at best, uncreative and naïve, and at worst misleading and incorrect, of banning proof of work mining and banning the trading of proof of work currencies from exchange platforms (Wendl et al. 2023, p.10). Interestingly, this suggestion is reflected in recently proposed legislation in the United States, of taxing the energy usage of Bitcoin miners at a different rate to other users (Namabiampurath, 2023). Given the voluntary, decentralised and peer-to-peer nature of the Bitcoin network (Nakamoto 2008), both banning mining and trading is close to impossible (Crawley 2023). This was demonstrated by China's ban on Bitcoin mining in 2021, that merely caused a temporary drop in global energy consumption while mining equipment was relocated (Wendl et al. 2023) and with China remaining a significant part of the network (Crawley 2023). This suggests that further work needs to be done on the contributions "proof of stake" algorithms can make to the environment, particularly when compared to the proactive impact that "proof of work" algorithms are able to make covered in this work. If proof of stake's only contribution is that it uses less energy than "proof of work" but cannot make a positive contribution to the transition to renewable energy sources, this would suggest that any power directed towards "proof of stake" currencies is wasted energy.

Instead of the current approach of moving towards proof of stake crypto-currencies, policymakers and environmental activist need to step back from the widely held beliefs of crypto currencies. By doing so and learning about the positive impact bitcoin mining can play within both the improvement of the environment (through methane capture and use) and improvements in energy infrastructure (through monetising otherwise wasted electricity), they may even become cheerleaders for bitcoin. The policy implications are then quite unusual, given that the Texas demonstrates that open energy markets provide sufficient incentives, without the need for government support (Gkritsi, 2022). Instead, attention is needed on protecting companies investing in bitcoin mining and power infrastructure from the introduction of restrictive and counterproductive legislation, such as taxing power differently for different uses as outlined by Namabiampurath (2023). Even then, bitcoin miners' ability to locate themselves "behind the meter" (Sudock 2022) could allow them to benefit the grid and potentially circumnavigate such taxes. As a result, while policy to support bitcoin mining would likely be beneficial for many stakeholders, it is not essential. Rather than this form of legislation, there may simply be a need for legislation that protects bitcoin miners as well as bitcoin holders, that the asset they accumulate will not be legislated against in a way that makes it more difficult or expensive to use their bitcoin (selling, holding or spending). Schumacher (2017) and Nwanekezi et al. (2022) explored the importance of policy barriers in new energy infrastructure, so an ability to integrate bitcoin mining into proposals for new renewable energy projects is likely to be important to achieve government targets.

This review of Wendl et al. (2023) and extension of the role of bitcoin mining has providing two important findings in addition to the figures presented. As outlined earlier in this conclusion, while literature reviews represent an important part of the consolidation and development of academic knowledge, for newer subjects they provide less value by not considering recent development in the field. Literature reviews provide academics with a means to developing publications without the need to go through time consuming research ethics process and data collection, but there are other types of research they can conduct that

draws from more timely thinking on a topic. The previous section illustrates that literature reviews can provide a strong foundation to structure further investigations, that guide the researcher to publicly available, rich, qualitative data from experts, whether in the form of blogs, company websites or podcasts. Such sources can be freely accessed, reviewed and analysed (some of which are already transcribed) to paint pictures of topics being explored based on current practice. This data can also draw from actual businesses, that deliver outcomes and make money using this technology. When compared to mis-informed people attempting to slow progress and not contribute value to the energy infrastructure, publicising the voices of entrepreneurs working to improve the world should be something academics consider as having real value and impact.

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