Please cite this article in press as: de Vries, Bitcoin boom: what rising prices mean for the network's energy consumption, Joule (2021), https://doi.org/10.1016/j.joule.2021.02.006

Joule

CellPress

Commentary

# Bitcoin boom: what rising prices mean for the network's energy consumption

Q1 Alex de Vries[1,2,*]

Alex de Vries earned his MSc in Economics and Business from the Erasmus University Rotterdam in 2011. In 2014 he founded the blog digiconomist.net. This blog is a platform for research, dedicated to exposing the unintended consequences of digital trends. The blog is best known for featuring the Bitcoin Energy Consumption Index since late 2016, which has played a major role in the global discussion regarding
Q2 the sustainability of proof-of-work-based blockchains.

## Q3 INTRODUCTION

For the popular digital currency Bitcoin, the year 2021 started with the price of a single Bitcoin reaching progressively higher records in quick succession. In less than one month's time, the price of Bitcoin not only broke the previous record (from December 2017) of almost $20,000 per coin but doubled it, surging past $40,000 for the first time on January 8, 2021. In the same period, the demand for Bitcoin "mining" devices also increased rapidly. Within the Bitcoin network, these devices are used to participate in the process of creating new blocks for Bitcoin's underlying blockchain, with successfully created blocks providing a certain amount of bitcoins as a reward to the creator.[1] In January it was reported that Bitmain, one of the largest manufacturers of specialized Bitcoin mining devices, had sold out through August 2021 because of "overwhelming demand."[2]

The increasing popularity of Bitcoin mining quickly sparked a fresh debate on the energy use—and the resulting carbon footprint—of the Bitcoin network. Bitcoin mining devices require electrical energy to function, and all devices in the Bitcoin network were already estimated to consume between 78 and 101 terawatt-hours (TWh) of electricity annually prior to the latest surge in the price of Bitcoin (Figure 1). With a growing number of active machines, the network as a whole also requires more power to operate.

This Commentary examines how to estimate the amount of electricity the Bitcoin network consumes for a given Bitcoin price level. Additionally, the article explores the implications of this energy consumption for the environment and broader economy and discusses how policymakers can limit the network's growing energy demands.

## PREDICTING FUTURE BITCOIN NETWORK ELECTRICITY CONSUMPTION

In order to assess what a certain price level might mean for the energy hunger of the Bitcoin network, it is crucial to first understand the relationship between these two variables. As noted, Bitcoin miners are rewarded with bitcoins for successfully creating new blocks for Bitcoin's blockchain. In May 2020, this reward amounted to 6.25 newly minted bitcoins per block, plus a variable amount depending on the Bitcoin transactions that get processed in the block. In December 2020, transaction fees made up for about 10% of the total overall miner income.[3]

These combined rewards provide a strong incentive to participate in the mining process, but the Bitcoin protocol also purposely makes it difficult for miners to actually obtain these rewards. To successfully create a new block for the blockchain, the block has to satisfy a set of requirements. For the miners, this translates into a process of trial and error. As of January 11, 2021, it is estimated that all miners combined make over 150 quintillion (blockchain.com/charts/hash-rate) attempts every second of the day to produce a valid new block. Moreover, the Bitcoin protocol self-adjusts the difficulty of meeting these requirements to ensure that, on average, only one block is created every 10 min.[1] All of the mining devices in the network are constantly competing with each other to be the first to produce a valid new block. With the chance of success being random, a miner's share of the total available miner income will average to the proportional share of the total computational power in the network owned.

Bitcoin's price directly effects the value of the mined coins and therefore the amount of resources miners can afford to spend on mining. Given that Bitcoin mining is a competitive market,

Please cite this article in press as: de Vries, Bitcoin boom: what rising prices mean for the network's energy consumption, Joule (2021), https://doi.org/10.1016/j.joule.2021.02.006



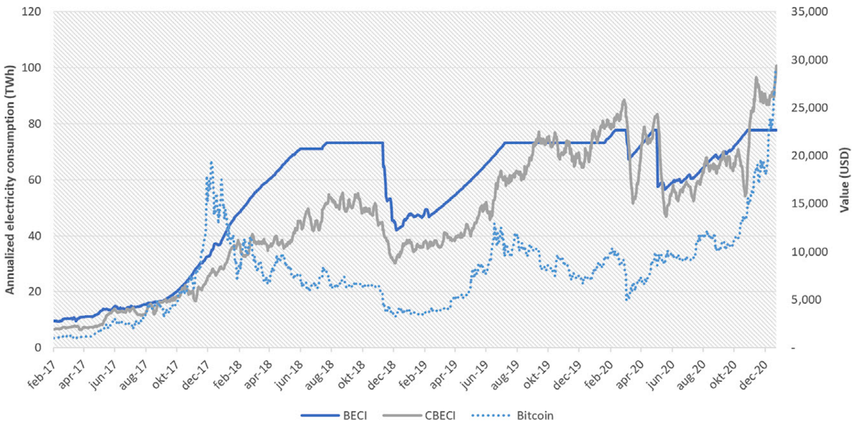


**Figure 1. Historic Bitcoin energy consumption estimates and price development**

The fluctuations in Bitcoin price (from finance.yahoo.com/quote/BTC-USD), along with estimates of Bitcoin's energy consumption (in annualized TWh) from the Bitcoin Energy Consumption Index (BECI) (bitcoinenergyconsumption.com) and the Cambridge Bitcoin Electricity Consumption Index (CBECI) (cbeci.org) since the start of 2017 to the end of 2020.

economic theory suggests that it should cost a bitcoin to mine a bitcoin.[4] If it costs any less than one bitcoin to mine a bitcoin, miners can profit by adding more units of computational power to the network. The opposite is also true because miners would be operating at a loss and start removing units of computational power from the network if mining costs exceed one bitcoin. As previously noted by de Vries, "these market forces drive the industry towards an equilibrium where firms will earn zero economic profit."[5]

This dynamic makes it possible to estimate the amount of energy the network is consuming given a certain amount of total miner income. Although we should not expect a market to be in perfect equilibrium because circumstances are constantly changing, we do expect total miner expenses to gravitate toward the total amount of miner income as well. Knowing how miner expenses will develop does not immediately give us an energy consumption estimate, but fortunately, the cost structure of mining is extremely simplistic. A miner only requires a machine capable of mining (which can be a central processing unit, graphic processing unit, or a specialized application-specific integrated circuit) and electricity to run the device. For this reason, the primary cost components of participating in the mining process are only hardware and energy. de Vries previously estimated that, in the long run, the share of electricity costs in the total costs of mining is around 60%.[5]

If, on top of the previous assumption, we assume miners pay around $0.05 per kilowatt-hour (kWh) of electrical energy on average, we can estimate the network's energy requirement at a given amount of miner income. With a Bitcoin price of $42,000 (Bitcoin's all-time high as of January 10, 2021) and transaction fees comprising 10% of total miner income, miners will earn around $15.3 billion annually (6.25 coins per block * 52,560 blocks per year / 0.9 * $42,000). With 60% of this income going to pay for electricity at a price of $0.05 per kWh, the total network could consume up to 184 TWh per year (sensitivities to different assumptions are shown in Table 1); this is not far from the amount of energy consumed by all data centers globally (200 TWh per year).[6]

## ADOPTION SPEED OF MINERS AND HARDWARE CAPACITY RESTRICTIONS

Economic models do not indicate exactly when the network will reach an annual energy consumption of 184 TWh, but miners have a strong incentive to add new mining devices as fast as possible. As the total amount of computational power in the network grows, the proportional share of each individual device declines over time. The number of bitcoins a device is expected to mine therefore declines as well, meaning that the first person to use a new device type will always reap significantly more rewards than the last. In fact, it is mostly due to limits in the availability of hardware that the network does not reach these levels of energy consumption overnight. Miners have some flexibility in the way their devices are set up, so there is likely to be a swift effect from miners boosting (overclocking) their device's performance. However, this effect is equally likely to be limited as devices become unstable and/or require additional cooling if pushed too far. The speed at which the network's energy consumption grows then depends on the availability of previously obsolete device models (that can operate profitably again) and the rate at which newer device models can be produced. With Bitmain having sold out up to the third quarter of 2021 by the start of the year, it could take several months, if not longer, for the network's energy consumption to reach the predicted level. Assuming that total miner income stabilizes at $15.3 billion annually, the network will ultimately consume 184 TWh per year.

## AN ABSENCE OF REFUNDS ENSURES MINING DEVICES WILL BE PRODUCED REGARDLESS OF PRICE DEVELOPMENTS

Because a vast number of new devices have now been ordered, a large part of the expected increase in energy consumption might already be "locked-in;" this means that even if Bitcoin price falls by 25% or more (on January 11, the Bitcoin price fell to $31,000 per coin before recovering to $35,000), the estimations of the network's future energy

Please cite this article in press as: de Vries, Bitcoin boom: what rising prices mean for the network's energy consumption, Joule (2021), https://doi.org/10.1016/j.joule.2021.02.006



**Table 1. Bitcoin annual energy consumption (TWh) model sensitivity table**

| BTC (USD) $ 32,000 | Price per kWh (USD) 0.03 | 0.04 | 0.05 | 0.06 | 0.07 |
|---|---|---|---|---|---|
| Electricity cost 50% | 195 | 146 | 117 | 97 | 83 |
| 55% | 214 | 161 | 128 | 107 | 92 |
| 60% | 234 | 175 | **140** | 117 | 100 |
| 65% | 253 | 190 | 152 | 127 | 108 |
| 70% | 273 | 204 | 164 | 136 | 117 |

| BTC (USD) $ 42,000 | Price per kWh (USD) 0.03 | 0.04 | 0.05 | 0.06 | 0.07 |
|---|---|---|---|---|---|
| Electricity cost 50% | 256 | 192 | 153 | 128 | 110 |
| 55% | 281 | 211 | 169 | 141 | 120 |
| 60% | 307 | 230 | **184** | 153 | 131 |
| 65% | 332 | 249 | 199 | 166 | 142 |
| 70% | 358 | 268 | 215 | 179 | 153 |

| BTC (USD) $ 37,000 | Price per kWh (USD) 0.03 | 0.04 | 0.05 | 0.06 | 0.07 |
|---|---|---|---|---|---|
| Electricity cost 50% | 225 | 169 | 135 | 113 | 96 |
| 55% | 248 | 186 | 149 | 124 | 106 |
| 60% | 270 | 203 | **162** | 135 | 116 |
| 65% | 293 | 219 | 176 | 146 | 125 |
| 70% | 315 | 236 | 189 | 158 | 135 |

| BTC (USD) $ 47,000 | Price per kWh (USD) 0.03 | 0.04 | 0.05 | 0.06 | 0.07 |
|---|---|---|---|---|---|
| Electricity cost 50% | 286 | 214 | 172 | 143 | 123 |
| 55% | 315 | 236 | 189 | 157 | 135 |
| 60% | 343 | 257 | **206** | 172 | 147 |
| 65% | 372 | 279 | 223 | 186 | 159 |
| 70% | 400 | 300 | 240 | 200 | 172 |

The table shows how various assumptions on the share of electricity costs in the total costs of mining, as well as the average price of electricity (in USD per kWh), influence the expected future energy consumption of the Bitcoin network at four different price levels. For every scenario, it is assumed that fees make up 10% of the total miner income next to a fixed block reward of 6.25 bitcoins.

consumption do not necessarily have to revised by the same amount. This "lock-in" effect is the result of Bitmain's policy (and similar ones of other manufacturers) stating that "cancellation or refund requests will not be entertained."[7] As such, upon submitting an order, the equipment becomes a "sunk cost." Once a sunk cost has
Q4 been incurred, it can no longer be recovered; thus, it should play no further role in the decision-making process of a rational economic agent. Just like any other miner who already has devices running, those who have ordered and paid for their new devices should base their decision to (continue to) mine on prospective costs, which primarily only include electricity costs. For miners who only care about electricity costs, a Bitcoin price of $25,200 (assuming $0.05 per kWh) is sufficient to sustain an annual electricity consumption of 184 TWh.

## LIMITS TO THE PREDICTABILITY OF BITCOIN'S FUTURE ELECTRICITY CONSUMPTION

There is no way of knowing the precise amount of future energy consumption that has been "locked-in" because of non-refundable orders, but with production lines guaranteed to run at maximum capacity for a majority of 2021, it is unlikely to be an insignificant amount. In any case, we should be mindful of this effect when considering a drop in Bitcoin price, though a scenario similar to that which followed the Bitcoin price peak of 2017 could still occur. After the Bitcoin price got close to $20,000 for the first time in 2017, the market experienced a rapid and steep decline. By the end of 2018, the value of Bitcoin had dropped by more than 80% since the price peak. A Bitcoin price crash of a similar magnitude in 2021 would reduce the network's energy consumption from the current estimates (Figure 1). If total annual miner income falls to $3 billion (corresponding to a Bitcoin price of around $8,000 depending on the transaction fee percentage at this point), this could only sustain an energy consumption of at most 60 TWh per year (assuming the entire amount is used to pay for electricity).

We also have to guard against overestimating the network's future energy consumption. In the past, the results of studies like these have been incorrectly extrapolated to make statements on the network's future energy consumption. The relationship between the network's energy consumption and miner income is mutual, meaning that miners require a certain amount of income to support a given level of energy consumption. This article is limited to examining what the potential future implications are in terms of energy consumption assuming stability in current miner income levels. Long-term forecasts require more detailed modeling, and even the simple model presented in this article should account for relevant changes in Bitcoin mining rewards. Bitcoin's fixed block reward has been set to halve every 210,000 blocks (roughly every four years), which will happen again in 2024. Although typical useful lifetimes of mining devices are too short[8] for this reward reduction to be relevant in this article, it is something to be considered in future research along with the growing importance of variable transaction fees.

Furthermore, future research might study the effect of network size on the average price of electricity. In the short run, one might expect the average price of electricity to go up as the network grows because there is a finite source of the cheapest electricity. However, the recent growth of cryptocurrency mining in (sanctioned) countries like Iran[9] (where miners can obtain oil-fueled electricity for less than $0.01 per kWh[9]) suggests the possibility that new mining locations might drive the average price of electricity down instead. In any case, the chosen rate of $0.05 per kWh (commonly used in research on the topic in recent years)

Please cite this article in press as: de Vries, Bitcoin boom: what rising prices mean for the network's energy consumption, Joule (2021), https://doi.org/10.1016/j.joule.2021.02.006



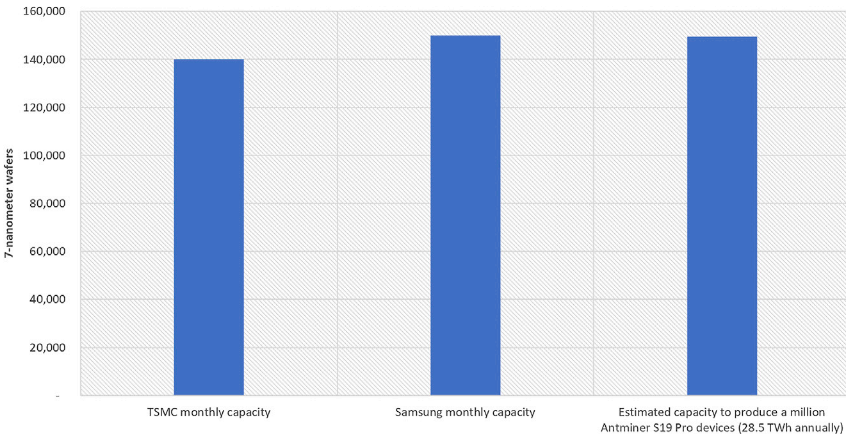


**Figure 2. Comparison of chip production capacity versus mining device chip production requirements**

This figure shows the monthly 7 nanometer (nm) wafer capacity at the foundries of Taiwan Semiconductor Manufacturing Company (TSMC) and Samsung (wccftech.com/amd-7nm-wafer-production-set-to-double-in-2 h-2020-7nm-capacity-at-tsmc-currently-fully-booked/). These companies are the only ones capable of mass-producing 7 nm nodes (am.miraeasset.com.hk/insight/intel_7nm_delay/). The output needed to produce one million Antminer S19 Pro devices is calculated on the assumption that the required die size is 5 × 5 mm (in line with the Antminer S17 series) (bitcointalk.org/index.php?topic = 5307087.0) and that each 300 mm wafer yields 2,288 viable dies (caly-technologies.com/die-yield-calculator/) on a defect density of 0.09 (anandtech.com/show/16028/better-yield-on-5nm-than-7nm-tsmc-update-on-defect-rates-for-n5). Each Antminer S19 Pro requires 342 chips (chainnews.com/zh-hant/articles/648268505750.htm) and runs on 3,250 W.

is likely still a conservative value for the network size considered in this article given that a recent survey found miners pay a global average of $0.046 per kWh.[10]

Lastly, it should be noted that this article generally assumes a market with rational agents; however, in reality, miners might make decisions like (temporarily) operating at a loss if they speculate on (further) price increases. This speculation might also increase the aforementioned "lock-in" effect if miners order an excessive amount of mining devices in anticipation of a higher Bitcoin price, though this will also depend on the limits of the production capacity of mining device manufacturers and their suppliers (see next section).

## ENVIRONMENTAL IMPACT AND BROADER CONSEQUENCES

Having an estimate of Bitcoin's future energy consumption also permits a ballpark estimate for the network's future carbon footprint. To this end, the work of Stoll et al.[11] demonstrated that Bitcoin mining had an implied carbon intensity of 480–500 g of CO2 per kWh (gCO2/kWh) consumed. Assuming this number remains constant at 490 gCO2/kWh as the network's energy demand increases, a total energy consumption of 184 TWh would result in a carbon footprint of 90.2 million metric tons of CO2 (Mt CO2), which is roughly comparable to the carbon emissions produced by the metropolitan area of London (98.9 Mt CO2, according to citycarbonfootprints.info). This number might be higher or lower depending on the locations chosen for Bitcoin mining. Although fossil-fuel-dependent countries like Iran have recently gained popularity as mining sites,[9] market miners might also try to leverage "greener" sources of power.

In any case, the remainder of the cryptocurrency ecosystem would still have to be added to the total environmental impact of the sector. Recent research found that other understudied cryptocurrencies such as Ethereum and Litecoin added "nearly 50% on top of Bitcoin's energy hunger."[12] Moreover, specialized Bitcoin mining devices cannot be repurposed, potentially resulting in a substantial amount of electronic waste once they become obsolete in several years' time.[8]

On top of the environmental impact of cryptocurrency mining, the effects of the sector's energy-hunger might also spill over to other parts of the economy. Prior to the latest surge in Bitcoin price, it was already reported that there was a global shortage of chips for an array of electronic devices.[13] The economic recovery after the COVID-19 crisis has led to increased consumer demand, resulting in chip shortages and delays in manufacturing. These shortages are also affecting the production of (self-driving) electric vehicles, which will play an important part in meeting global goals for climate change, as well as personal electronics required to work from home. Because the manufacturers of Bitcoin mining devices need a substantial number of chips to produce these machines, this will only exacerbate the shortage. To produce just one million units of Bitmain's most powerful mining device (the Antminer S19 Pro), which can consume 28.5 TWh of electrical energy annually, Bitmain would have to book a full month of 7 nanometer (nm) capacity at its supplier, Taiwan Semiconductor Manufacturing Company (together with Samsung, currently the only companies capable of mass-producing 7 nm chips) (Figure 2).

It might also be a concern that a country like Iran has adopted cryptocurrency mining as a way to boost revenues while its oil exports suffer from international sanctions. Cheap energy has lured in many cryptocurrency miners, and the mining activity in Iran now represents 8% of the total computational power in Bitcoin's network.[9] If Bitcoin is enabling Iran to circumvent economic

Please cite this article in press as: de Vries, Bitcoin boom: what rising prices mean for the network's energy consumption, Joule (2021), https://doi.org/10.1016/j.joule.2021.02.006



sanctions, this could pose a threat to international safety, given that these sanctions were imposed to prevent the nation from developing military nuclear capability.

## CONSIDERATIONS FOR POLICYMAKERS

Given the growing implications of the cryptocurrency mining industry, policymakers might feel increasingly pressured to intervene. At a local level, this has already occurred in places such as Québec (Canada) and Iran. In Québec in 2018, the Canadian power company Hydro-Québec and the independent Québec Energy Board decided to impose a moratorium on new cryptocurrency mining operations, after a significant number of applications threated to destabilize the local grid.[14] More recently, in January 2021, Iran decided to confiscate mining equipment as the country suffered from outages blamed on cryptocurrency mining activities.[9]

Despite the fact that, in both examples, policymakers did not decide to take action because of environmental concerns, the examples illustrate how policymakers might have multiple options in putting a halt to cryptocurrency mining. Although Bitcoin might be a decentralized currency, many aspects of the ecosystem surrounding it are not. The competitive Bitcoin market drives miners to take advantage of economies of scale in lowering costs, which also makes it harder for them to operate under the radar. Large-scale miners can easily be targeted with higher electricity rates, moratoria, or, in the most extreme case, confiscation of the equipment used. Moreover, the supply chain of specialized Bitcoin mining devices is concentrated among only a handful of companies. Manufacturers like Bitmain can be burdened with additional taxes like tobacco companies or be limited in their access to chip production. Policymakers can be even be more restrictive to certain cryptocurrencies by barring them from centralized digital asset marketplaces. Although the latter has no direct effect on mining, it can influence the value of a digital currency (and thus the associated mining rewards).

Policymakers should, however, be aware that there are also some boundaries to the policy options. Ultimately, any laptop or computer is theoretically capable of participating in cryptocurrency mining, and any location that has access to Internet and electricity might be used to host these devices. Miners could simply move elsewhere under adverse policy decisions, or mining might become more decentralized (and harder to control) when large-scale mining facilities or manufacturers of specialized devices are severely restricted.

## CONCLUSION

As the price of Bitcoin rises, the negative externalities associated with Bitcoin mining increase in kind. This Commentary has shown how a simple economic model might be used to estimate the potential environmental impact of Bitcoin mining for a given Bitcoin price. These estimates reveal that the record-breaking surge in Bitcoin price at the start of 2021 could result in the network consuming as much energy as all data centers globally, with an associated carbon footprint matching London's footprint size. Beyond these environmental impacts, the production of specialized mining devices might exacerbate the global shortage of chips, which could effect the ability to work from home, the economic recovery after the COVID-19 crisis, and the production of electric vehicles. The increasing popularity of mining in countries like Iran could even threaten international safety. Policymakers are not completely powerless to stop this from materializing, but drastic joint and coordinated actions could be required to be effective.


1. Nakamoto, S. (2008). Bitcoin: A peer-to-peer electronic cash system. https://bitcoin.org/bitcoin.pdf.
2. Voell, Z. (2021). Bitcoin Mining Machine Shortage Worsens as Bitmain Sells Out Through August (Coindesk).
3. Voell, Z. (2021). Bitcoin Miners Saw 33% Revenue Increase in December (Coindesk).
4. Debreu, G. (1987). Theory of value: an axiomatic analysis of economic equilibrium 19. Dr (Yale Univ. Press).
5. de Vries, A. (2018). Bitcoin's Growing Energy Problem. Joule *2*, 801–805.
6. Kamiya, G. (2020). Data Centres and Data Transmission Networks. Int. Energy Agency. https://www.iea.org/reports/data-centres-and-data-transmission-networks.
7. Bitmain. (2017). Can I edit or cancel my orders?. https://support.bitmain.com/hc/en-us/articles/115000382293-Can-I-edit-or-cancel-my-orders-#:~:text=After%20an%20order%20is%20submitted,not%20pay%20for%20that%20order.
8. de Vries, A. (2019). Renewable Energy Will Not Solve Bitcoin's Sustainability Problem. Joule *3*, 893–898.
9. Arab News. (2021). Crypto-miners take down Iran electric grids, prompting crackdown. https://www.arabnews.com/node/1794836/middle-east.
10. Blandin, A., Pieters, G.C., Wu, Y., Eisermann, T., Dek, A., Taylor, S., and Njoki, D. (2020). 3rd global cryptoasset benchmarking study. https://www.jbs.cam.ac.uk/faculty-research/centres/alternative-finance/publications/3rd-global-cryptoasset-benchmarking-study/.
11. Stoll, C., Klaaßen, L., and Gallersdörfer, U. (2019). The Carbon Footprint of Bitcoin. Joule *3*, 1647–1661.
12. Gallersdörfer, U., Klaaßen, L., and Stoll, C. (2020). Energy Consumption of Cryptocurrencies Beyond Bitcoin. Joule *4*, 1843–1846.
13. Jin, H., Busvine, D., and Kirton, D. (2020). Analysis: Global chip shortage threatens production of laptops, smartphones and more (Reuters).
14. de Vries, A. (2020). Bitcoin's energy consumption is underestimated: A market dynamics approach. Energy Res. Soc. Sci. *70*, 101721.


[1]Digiconomist, Almere, the Netherlands

[2]De Nederlandsche Bank, Amsterdam, the Netherlands

*Correspondence: alex@digiconomist.net

https://doi.org/10.1016/j.joule.2021.02.006