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## Supplemental Information

# Energy Consumption of Cryptocurrencies Beyond Bitcoin

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## Supplemental Data Items

**Table S1. Details on the studies depicted in overview of Bitcoin energy consumption estimates, related to Figure 1 in the main body.**

Figure 1 in the Commentary's main body depicts the electricity consumption estimates of the Bitcoin network. Table S1 provides details on the studies depicted in Figure 1 (from 01/2017 until 03/2020). Most study results reflect the electricity consumption of the Bitcoin network at a specific date. Some studies state an average consumption or ranges over a period of time, as highlighted in the third column of Table S1. The indexed hash-rate (the computing power of the network) charted in Figure 1 is retrieved from Blockchain.com[1].

| Study | Date | Observation | Estimate [MW] |
|---|---|---|---|
| Vranken[2] | 01/01/2017 | Cutoff date | 100-500[a] |
| Bevand[3] | 02/26/2017 | Cutoff date | 470-540[b] |
| | 07/28/2017 | | 816-944[b] |
| | 01/11/2018 | | 2,100[b] |
| De Vries[4] | 03/2018 | Cutoff date | 2,550-7,670[c] |
| McCook[5] | 06/19/2018 | Cutoff date | 12,080[d] |
| Mora et al.[6] | 2017 | Period average | 13,010[e] |
| Krause and Tolaymat[7] | 2017 | Period average | 948[f] |
| | 2018 (first half-year) | | 3,441[f] |
| Stoll et al.[8] | 12/2016 | Cutoff date | 345[g] |
| | 12/2017 | | 1,637[g] |
| | 11/2018 | | 5,232[g] |
| Köhler and Pizzol[9] | 2018 | Period average | 3,571[h] |
| Digiconomist[10] | 03/2017-03/2020 | Period range | 1,182-8,272[i] |
| CBECI[11] | 01/2017-03/2020 | Period range | 847-8,095[j] |
| This study | 03/27/2020 | Cutoff date | 4,291 |

**Table S1 | Details on the studies depicted in overview of Bitcoin energy consumption estimates.** Estimates are presented in megawatt (MW). a. range derived from lower limit (miners use state-of-the-art hardware) and upper limit (miners spend revenues on energy), b. ranges calculated by a bottom-up approach assuming different hardware mixes, c. lower limit assumes miners use state-of-the-art hardware; upper limit assumes miners spend 40% of all revenues on hardware and 60% on electricity and represents a scenario possibly applicable in the future, d. only figure that includes the power spent on manufacturing of the mining hardware, which represents 57% of this total power estimate; power usage effectiveness (PUE) of 1.25 considered, e. calculation based on the flawed assumption that the number of transactions drives power consumption, f. bottom-up approach deploying hash-rates and miners device efficiencies, g. bottom-up approach; PUE of 1.05 considered, h. 27.14 milliwatt hours/terahash; translated in monthly averages with total annual as of 2018, i. historical development of monthly averages; estimates calculated by assuming 60% of revenues are spent on operational costs incl. electricity, hardware, and cooling costs, j. Historical development of monthly averages using a bottom-up approach; PUE of 1.1 considered.

**Table S2. Data sources of input parameters, related to Table 1 in the main body.**

Table 1 in the main body of the Commentary displays the top 20 mineable currencies with their respective algorithms, hash-rates of the networks, the efficiency of suitable hardware, and rated power of the networks. Table S2 lists the data sources of underlying input parameters.

| Input parameter | Data source |
|---|---|
| Market capitalization | CoinMarketCap[12] |
| Hash algorithms | WhatToMine[13] |
| Network hash-rate: BTC, ETH, BCH, BSV, LTC, XMR, DASH, ETC, ZEC, DOGE, BTG | CoinMetrics.io[14] |
| Network hash-rate: RVN, MONA, DGB, ZEN | CoinWarz[15] |
| Network hash-rate. KMD, BCN | WhatToMine[13] |
| Network hash-rate: DCR | dcrstats.com[16] |
| Network hash-rate: BTM | tokenview.com[17] |
| Network hash-rate: SC | siastats.info[18] |

**Table S2 | Data sources of input parameters of Table 1.**

**Table S3. Reference hardware for ASIC-compatible algorithms, related to Table 1 in the main body.**

For each currency we decide – depending on the ASIC-resistance of the PoW-algorithm – which hardware to select. If the algorithm is ASIC-compatible, we rely on hardware estimates of WhatToMine[13]. Table S3 depicts ASIC-hardware used in our calculation. We verified the data for speed and energy consumption with ASICMinerValue[19]. We validated the collected data with information on manufacturers' websites if a device was not available on both ASICMinerValue and WhatToMine.

| Algorithm | Hardware | Speed [Hashes/s] | Rated Power [W] | Efficiency [Hashes/s/W] |
|---|---|---|---|---|
| SHA-256 | Bitmain Antminer S17 Pro 53TH | 5.3E+13 | 2,094 | 2.53E+10 |
| Scrypt | Innosilicon A4+ LTCMaster | 6.2E+08 | 750 | 8.27E+05 |
| X11 | Spondoolies SPx36 | 5.4E+11 | 4,400 | 1.22E+08 |
| Blake | Bitmain Antminer DR5 | 3.4E+13 | 1,800 | 1.89E+10 |
| Equihash | Innosilicon A9++ ZMaster | 1,4E+05 | 1,550 | 9.00E+01 |
| CryptoNight | Innosilicon A8+ CryptoMaster | 2.4E+05 | 480 | 5.00E+02 |
| Tensority | Bitmain Antminer B7 | 9.8E+04 | 528 | 1.82E+02 |
| Lyra2REv2 | FusionSilicon X1 Miner | 1.296E+10 | 1,110 | 1.17E+07 |
| Sia | Obelisk SC1 Slim | 5.5E+11 | 450 | 1.22E+09 |

**Table S3 | Reference hardware for ASIC-compatible algorithms.**

**Table S4. Reference hardware for ASIC-resistant algorithms (GPUs), related to Table 1 in the main body.**

| | | | Ethash | | RandomX | | ZHash | | X16Rv2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Device name | | Release date | Speed [Mh/s] | Rated power [W] | Speed [h/s] | Rated power [W] | Speed [h/s] | Rated power [W] | Speed [Mh/s] | Rated power [W] |
| AMD | Radeon R9 380 | June 2015 | 19 | 140 | *n.a.* | *n.a.* | 16 | 120 | 3.9 | 130 |
| | Radeon R9 Fury | June 2015 | 29 | 220 | *n.a.* | *n.a.* | 32 | 240 | 13 | 270 |
| | Radeon RX 470 | June 2016 | 26 | 120 | 340 | 80 | 18 | 110 | 9.5 | 130 |
| | Radeon RX 480 | June 2016 | 29.5 | 135 | 470 | 90 | 21 | 120 | 11.5 | 140 |
| | Radeon RX 570 | April 2017 | 27.9 | 120 | 390 | 80 | 19 | 100 | 10 | 120 |
| | Radeon RX 580 | April 2017 | 30.2 | 125 | 470 | 90 | 21 | 110 | 11.5 | 130 |
| | Radeon RX Vega 56 | August 2017 | 36.5 | 180 | 1040 | 150 | 34 | 230 | 16 | 230 |
| | Radeon RX Vega 64 | August 2017 | 40 | 200 | 1160 | 160 | 38 | 250 | 18 | 250 |
| | Radeon RX 5700XT | July 2019 | 51.5 | 140 | *n.a.* | *n.a.* | *n.a.* | *n.a.* | *n.a.* | *n.a.* |
| | Radeon VII | February 2019 | 78 | 230 | 1400 | 170 | 49 | 180 | 23 | 240 |
| Nvidia | GTX 1050 Ti | October 2016 | 13 | 80 | 200 | 60 | 19 | 80 | 8 | 80 |
| | GTX 1060 | August 2016 | 22.5 | 90 | 350 | 80 | 32.5 | 90 | 9.4 | 90 |
| | GTX 1070 | June 2016 | 30 | 130 | 560 | 120 | 56 | 130 | 18 | 130 |
| | GTX 1070 Ti | October 2017 | 30.5 | 130 | 640 | 120 | 59 | 130 | 19.5 | 130 |
| | GTX 1080 | May 2016 | 34.5 | 170 | 700 | 120 | 67 | 160 | 23 | 150 |
| | GTX 1080 Ti | September 2017 | 45.5 | 180 | 1030 | 160 | 86 | 200 | 31 | 190 |
| | GTX 1660 | March 2019 | 20.5 | 90 | 530 | 90 | 37 | 90 | 17 | 90 |
| | GTX 1660 Ti | February 2019 | 25.7 | 90 | 580 | 90 | 39 | 90 | 17.2 | 90 |
| | RTX 2060 | January 2019 | 27.6 | 130 | 600 | 110 | 57 | 130 | 22 | 130 |
| | RTX 2070 | October 2018 | 36.9 | 150 | 700 | 140 | 62 | 150 | 24.5 | 150 |
| | RTX 2080 | September 2018 | 36.9 | 190 | 1000 | 150 | 88 | 190 | 33.5 | 190 |
| | RTX 2080 Ti | September 2018 | 52.5 | 220 | 1380 | 190 | 100 | 220 | 41 | 220 |
| | **Overall Efficiency [Hashes/s/W]** | | **228,128.83** | | **6.02** | | **0.30** | | **116,006.10** | |

**Table S4 | Reference hardware for ASIC-resistant algorithms.** For algorithms that are ASIC-resistant, Table S4 depicts the hardware selection, release date, hash-rates, and energy consumption for four ASIC-resistant algorithms. In the bottom line, the overall efficiency of all cards is displayed for the respective algorithm. We rely equally on all 22 GPUs suggested by WhatToMine. Some values are not available on WhatToMine. We marked them as *n.a.* (not available) and exclude them in our estimates.

## Remarks on data validity

- **Device selection**: We select ASIC hardware and graphics cards according to data provided by WhatToMine. For ASIC-compatible algorithms, we assume one representative device per algorithm (see Table S3). For ASIC-resistant algorithms, we take a multitude of suitable devices into account. Deciding on the distribution of hardware devices is highly challenging, primarily due to the vast number of GPUs available. We build our estimate on popular GPUs suited for mining as suggested by WhatToMine. It is noteworthy that considerable differences in efficiencies exist among the selected GPUs and that the release dates not necessarily correlate with efficiencies (for Ethash algorithm e.g., Nvidia GTX 1060 with release date 08/16 is 28% more efficient than Nvidia RTX 2080, which was released more than two years later in 09/18). To account for the diversity in the graphics card ecosystem, we assume an equal distribution across the listed graphics cards. This assumption we have to make on the GPU distribution due to limited empirical evidence adds a certain degree of uncertainty. Assuming a different distribution would change the absolute results according to the efficiencies of overweighed GPUs.

- **Optimized devices**: WhatToMine provides hash-rates and energy usage of GPUs with settings that enhance the efficiency of the device. This is facilitated by increasing or decreasing GPU clock speed, lowering voltage, or installing a custom basic input/output system (BIOS). Generally, this affects our estimates as not all miners might apply these settings, and as not all GPUs are affected by such optimization equally (e.g., due to chip quality). Future research may validate these estimates and provide more accuracy here by physically measuring the energy efficiency of different GPUs in certain configurations.

- **Further inefficiencies**: Our estimate does not include power usage effectiveness (e.g., losses due to cooling, or cable and transformer losses), or other auxiliary energy costs (e.g., GPUs require additional hardware such as a mainboard or CPU). Additionally, the rated power is not equal to measured (and consumed) power of devices. Such aspects add further uncertainty to the absolute energy consumption figures per single cryptocurrency, as we directionally underestimate the energy consumption compared to other approaches (as seen in Table S1, and as suggested by the comparison of our results with more sophisticated methodologies for Bitcoin (see main body for details)). However, as this inaccuracy applies to all examined cryptocurrencies, potential changes in absolute numbers would likely impair the estimates of all cryptocurrencies in a similar manner, and not impair the relative shares. Future research into understudied coins (besides Bitcoin) may provide more certainty on absolute figures.

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