Bitcoin: Cryptopayments Energy Efficiency

Michel KHAZZAKA*

khazzaka@valuechain.pro

April 20, 2022

Abstract

Bitcoin introduced a cryptographic peer-to-peer version of money that allows online payments to be sent directly from one party to another without going through a financial institution. Many recent studies evaluated and criticised Bitcoin's energy consumption[1] through its Proof of Work (PoW) consensus mechanism without evaluating its efficiency compared to classical electronic payment system.

Based on physics, information science and economics, we compute and compare the energy consumption and define what is the energy efficiency of both the current monetary payment system and Bitcoin cryptopayment system. We demonstrate that Bitcoin consumes 56 times less energy than the classical system, and that even at the single transaction level, a PoW transaction proves to be 1 to 5 times more energy efficient. When Bitcoin Lightning layer is compared to Instant Payment scheme, Bitcoin gains exponentially in scalability and efficiency, proving to be up to a million times more energy efficient per transaction than Instant Payments.

Introduction

Bitcoin is designed and built to function as a world global currency and an online payment system. This is the promise declared in the 1st sentence of the Bitcoin white paper abstract: *"A purely peer-to-peer version of electronic cash would allow online payments"*. While Bitcoin is still representing ≈ 42% of the total cryptocurrencies' market cap, many of its detractors continue their criticism of its Proof of Work consensus mechanism accusing it of being power-hungry up to megalomania. The central bank of Netherlands DNB compared its energy consumption to a whole country like Denmark or the Netherlands in the De Nederlandsche Bank paper "*The carbon footprint of bitcoin*"[2]. Although most[3] central banks do not recognise Bitcoin as legal tender, yet they are convinced of the capabilities of the distributed ledger technology[4] (DLT) in payments, banking and finance. The DNB paper did not compare Bitcoin PoW energy efficiency with any parts of the classical monetary and payments system. What is needed is a correct evaluation of Bitcoin functions and their energy consumption compared to their counterparts in the classical electronic cash and payments systems. Many have tackled this challenge without completing it. Changpeng Zhao the founder of Binance recently asked for any data about payments' *vs.* cryptopayments energy consumption and *Institut Sapiens* the French think "tech" recommended in its publication "*Bitcoin, totem & tabou*" for this work to be performed: *"banking industry, whose energy cost is considerable but never evaluated, recognized, nor published. It would be interesting to calculate the energy cost of the banking sector…"*

[1] In march 2022, EU Markets in CryptoAssets regulation (MiCA) discussed banning completely proof of work based crypto-assets for claims of energy inefficiency.

[2] By Authors Juan Pablo Trespalacios and Justin Dijk, 2021

[3] Central banks of Salvador and Central African Republic recognised Bitcoin as legal tender other countries have regulations that recognize Bitcoin as analogue to foreign currencies such as Russia.

[4] See our Cryptopayments Glossary issued in 2020 by France Payments Forum *(in French)* for the difference between blockchain and DLT as well as the definition of legal tender etc.

The weaknesses in the previous studies are as follows:

- ***Use of inaccurate numbers or incomplete methodologies:*** for example the Cambridge Bitcoin Electricity Consumption Index (CBECI) which is based on a world average of electricity prices in USD and an average distribution of mining hardware leads to inaccurate results varying between −50% (lower bound) up to +120% (upper bound). This is a known limitation of the CBECI methodology in addition to its lack of comparing 2 similar systems efficiency. This paper will address both of these issues.
- ***Often partial or anti-bitcoin position***: and usually do not account for both monetary systems and payments systems. For instance the central bank paper by the DNB *"The carbon footprint of bitcoin",* compares Bitcoin energy consumption to the debit card payment system alone basing their statements on the Cambridge index and the study "*The Energy Consumption of Blockchain Technology: Beyond Myth*" [5]. Yet card payments are just an intermediary step of the payment transaction, they mainly provide an authorisation of a transaction and will at least require later inter-banking clearing and settlement to become final. On the other hand a bitcoin transaction is final and covers end-to-end steps of the transaction, so the comparison is very incomplete.

It's essential to compare Bitcoin energy consumption with all the aspects of the classical monetary payment system. This covers: banknotes and coins cash management in ATM systems, card payments, point of sale (POS) payments, banking and inter banking energy consumption etc. (*see* METHODOLOGY *below*)

We've endeavoured in our paper to answer mathematically and scientifically all these challenges for the benefit of decision makers, researchers, politicians, legislators and industry representatives.

SCIENTIFIC APPROACH

In order to study the energy consumption of Bitcoin PoW cryptocurrency system and the classical electronic system, we start by setting the governing mathematical and scientific equations into play that will be used hereafter.

Work in physics, is the energy transferred to or from a system via the application of *force* along a displacement in spacetime[6]. In our case, a payment *work* is to transfer an amount of value *money* from a *payer* to a *payee* along a displacement over *time*. Note that by nature an electronic transaction (*noted* Tx) can travel the globe in near real-time so the notion of displacement in *distance* measured in *kilometer* has a lower weight in the equation compared to the displacement in *time* which will be more weighing in the equation. Here *time* is the time span δt required to finish the payment *work*.

> A payment *work* is to transfer an amount of value called *money* from a *payer* to a *payee* along a displacement over *time*. [A]

The physical force[7] applied is provided mainly through an electrical force causing a differential of energy. From Newton's second law, it can be shown that *work* on a free (no fields), rigid (no internal degrees of freedom) body, is equal to the change in kinetic energy E_k corresponding to the linear velocity and angular velocity of that body $W = \Delta E_k$, where the *energy* is the quantitative property that must be transferred to the system to perform *work* (and/or to heat it)[8]. It's important to insist that energy is a conserved quantity; the law of conservation of energy states that energy can be converted in form, but not created or destroyed. Energy like *work* is also measured in Joule in the international system[9] but can be also measured in $Watt \times hour$ or kWh[10] which is 1000Wh. *Power* is the amount of energy transferred or converted per *time* unit:

[5] The research used by DNB to criticise the PoW actually concludes by stating: *"While their energy consumption is, indeed, massive, particularly when compared to the number of transactions they can operate, we found that they do not pose a large threat to the climate, mainly because the energy consumption of PoW blockchains does not increase substantially when they process more transactions"*. But the central bank seemed to have missed this detail.

[6] In its simplest form, it is often represented as the product of force and displacement.

[7] Power and energy are scalar quantities in opposite to the vectorial form of the *force*.

[8] *Heat* and mechanical *work* are special forms of a same value that is conserved and is called *energy* by Lord Kelvin and he called *thermodynamics* the science that studies it.

[9] One Joule is the energy transferred to an object by the work of moving it a distance of one metre against a force of one newton.

[10] The conversion rule is 1kWh = 3 600 000 Joules or 1Wh = 3600J

$$Power = \frac{Energy}{Time} = \frac{dW}{dt} = \overline{F}.\overline{v} \qquad [0]$$

Power is measured in Watt, joule per second and also in watt-hour/day or terawatt-hour per year (TWh/yr) for example when quantifying the electrical power of a data center or a country. For instance, the energy consumed by the biggest datacenter in the world Equinix is 6.46 TWh/yr. The whole digital services on the internet consume 2,000 TWh/yr. In France digital services consume 10 TWh/yr which is 0.5% of total digital energy. We will use the megawatt: MW or the version of TWh/yr to measure power (power being an *energy consumption* here per year *see* [0]). We will also use kWh to measure energy.[11]

If $\Delta\mathscr{W}$ is the amount of work performed during a period of time of duration Δt, the average power P_{avg} over that period is given by the formula: $P_{\text{avg}} = \frac{\Delta W}{\Delta t}$.

What follows is the evaluation of the total consumed energy — that is power — of the monetary and payment systems worldwide compared to the energy consumption of Bitcoin.

Methodology

Money in economy is a measure of *work*[12], a value commonly called *price*[13]. Today money is considered to be a *financial instrument* issued by special monetary authorities such as central banks. In this paper, we argue that money can be qualified as a social contract, in essence, and thus can be defined as an *asset* with an *intrinsic power differential* between two economic agents. Traditionally money serves three functions: A *unit of account* as the foundation for economic metrology, a *medium of exchange* allowing to transform a value into *work* through space in the form of payment transactions and a *store of value* transporting this value through *time*. It can be easily seen that there are natural relations between *money*, *work*[14], *energy* and *power*.

The correct way to compare the classical monetary and payments system to Bitcoin is to compare all their common capabilities in terms of energy consumption[15]. Bitcoin serves as a:

- ***Monetary System***: issuing, burning, and circulating a cryptocurrency the *bitcoin* comparable to a central bank and its commercial banks issuing and distributing central bank money and commercial money.
- ***Means of Payment*** allowing the transfer of the cryptoasset *bitcoin* from a payer to a payee. The blockchain nodes serve as Payment Service Providers (PSP) similarly banks use card schemes, clearing and settlement mechanisms in the classical electronic payments industry with central banks.

The high level *work breakdown structure* of the monetary system can be simplified to the following functions:

- ***Monetary mass issuing*** and circulation of electronic money as well as the paper cash money and coins,
- ***Monetary distribution*** and lifecycle management through the economy based on supervised and regulated banking and financial institution service providers. This covers the physical form of money distribution in secured vehicles, vaults, and ATMs as well as an electronic form of money.
- ***Bookkeeping*** services with central bank accounts in wholesale using central bank money, and customer banking service bookkeeping in retail using core banking and online banking.
- ***Non-card payment*** services such as wire transfers, instalment automatic withdrawal like direct debit and other cross border or financial messages operations using Swift like third party provider in addition to Clearing and Settlement Mechanisms (CSM)

[11] To help understand the meaning of energy efficiency and *power* vs *energy*, note that burning 1Kg of coal releases much more energy than detonating 1Kg of TNT, but because the TNT reaction releases energy much more quickly, it delivers far more power than the coal.

[12] Plato defined it as a social convention while Aristotle as a measure of work See Aristotle's text here

[13] Some time the price of money means the interest rate

[14] And also Proof of Work PoW

[15] Its not in the scope of this paper to demonstrate that Bitcoin can serve as a currency and as a payment system. This is taken as a hypothesis and as the promise of its Blockchain as stated by Satoshi's white-paper.

- ***Card Payment*** services which include point of sales (POS) acceptance solutions and terminals, in addition to plastic card issuance and distribution, vicinity and online payments authorisation through a card scheme such as Visa, MasterCard or Carte Bancaire locally in France. It also includes the collection, clearing and settlement of those transactions through clearinghouses.

It's important to note that this paper is a global evaluation of payments worldwide, but in reality electronic payment systems are very fragmented and have different features and levels of efficiencies in different regions and countries around the world. In addition, the carbon foot print in CO2 for instance is not a reliable approach, since many companies and industries cover their carbon footprint by buying carbon credits. Their resulting carbon footprint is not their real carbon emission. The only scientifically reliable approach is by the computation of the *energy* in terawatt-hour (TWh) per year required by each system to function, and to compare their *work* accomplished in this pure form of input *energy* without taking into account the energy sources.

Scope

The chosen scope is to compare the "*Run*" of both crypto system and electronic system: this means to compare the energy consumption of the similar running operations and to leave out of scope the "*Build*"of each system, such as the manufacturing of ATM or miner units, the printing of banknotes and minting of coins. Although comparing the *Build* would have been beneficial for Bitcoin, it confers to it an unfair advantage. The issuance of bitcoins, called mining is included since it is a part of the running operations. The annual printing of banknotes and minting of coins are included, the cash distribution to ATMs and acceptance at electronic Point of Sales are also included to cater for the running electronic cash management. In addition all Payment Service Providers such as PayPal or any other marketplace payment or acceptance solution providers are left out of scope since these can be proposing cryptopayments solutions also, or can be replaced by blockchain wallets. So they are out of scope for simplification reasons and to ensure an homogenous methodology.

Most of the studies[16] available missed the point that it is a mistake to compare Bitcoin to Visa only since a card scheme does not execute a payment transaction from end to end as Bitcoin does. A card scheme ensures an authorisation in real time between the actors of the payments value chain: the bank of the cardholder called the Issuer and the merchant's Acquirer bank. But most[17] of the time the card scheme and the two banks need to settle the transaction in a delayed step using central bank money and sometimes between corespondent banks and different central banks in case of a cross border payment. In comparison, a transaction in bitcoin is final in near real-time, it is a push payment in only one step and the finality time is set to be about 10 minutes on average.

	Electronic System	*Crypto System*
Annual Issuing	Included	Included
Distribution	ATM and POS	N/A
Bookkeeping	Banks	Blockchain
Card payments	Acceptance, POS, authorisation & CSM	N/A
Other payments	Wiretransfer, debit, etc.	Cryptopayment
Cheques	Excluded	N/A
Finance services	Excluded (insurance & loans, etc.)	Excluded (DeFi)

In scope of capabilities included for energy assessment (highlighted) [T0]

Note that credit services are kept out of the scope of this study as well as DeFi financial services and web 3.0 use cases in order to focus on Bitcoin vs monetary and payments industries. Electronic cheques payments are also kept out of scope for simplification considering their adoption decrease (yet they still consume a considerable energy especially through printing, distribution and transit back to bank).

[16] For example DNB paper *"The carbon footprint of bitcoin"* or Arcane Research "*The State of Lightning*" — Oct 2021

[17] There exist a card payment mode called "*single mode*" that allows the cardholder to be instantly debited and the merchant account to be directly credited, but most of card payment transaction are in "*dual mode*" requiring to distinct steps: authorisation followed by collection of translations at the end of day, then a request to a clearing and settlement mechanism for compensation with central bank money. This distinction will not impact the energy consumption of the actors in general but only increase the speed of certain electronic payments compared to cryptopayments.

An approach that compares the transacted values in equivalent USD, not just transactions volumes is also unsuitable. Both systems, energy consumption won't be affected by transaction value. We have managed to exclude 100% of this research any exchange value rates and transacted amounts between Bitcoin and classical payments in dollar or euro for instance.

Finally energy sources and energy mix are kept out of scope for a total focus on the most fundamental questions: energy input & energy efficiency.

Our research follows the journey of a classical monetary & payments transaction from money issuing (yearly renewal) to its transit into an ATM or a cash point, followed by its acceptance in payment as cash. Then we switch to card payments energy of schemes like VISA and Mastercard, and ePoS acceptance, then we continue the journey through the banking system up the stream to central bank clearing and settlement mechanism. Finally we will consider the important update of classical payments into instant payments. For a Bitcoin transaction we will consider simply the total hardware used in mining and processing and compute the exact energy consumed by the Blockchain PoW. Later will we also assess the important improvement brought by Bitcoin Lightning.

At the end we will compute and compare the energy per a single transaction in both systems: Classical vs PoW then Instant vs Lightning. Then we will propose an energy efficiency equation that will allow us to arbitrate on both capacity , speed and energy consumption per transaction of both systems.

Here's a quick view of this paper's content:

Content Summary [T1]

Energy of Printing & Minting Cash

Let's start by calculating the energy consumption of the renewal rates of banknotes and coins. Note that we will not take into account the initial printing and minting of cash money according to our methodology of comparing only the run time energy consumption of both systems.

Although, you might consider that notes and coins are not electronic form of money and shouldn't be accounted for, yet this form of central bank money is used in retail electronic payments such as automated teller machines, or electronic point of sales terminals. Therefore they are accounted for in electronic payment transactions.

In order to estimate how much energy per yearner required yearly to print and mint we need to estimated the total number of coins and banknotes in use worldwide and the current renewal rate. These numbers are not easy to estimate given the lack of information from certain countries, the differences in currencies values and consumer preferences for coins or banknotes differ largely from a country to another. To succeed in this critical challenge and to reduce the error margin we've used 2 different sources and methodologies to narrow down the evaluation.

According to the ECB there are today 28.67 Billion banknotes and 141.97 Billion coins in circulation in eurozone representing respectively €1.587 Billion and €31.426 Billion. After the COVID period the demand for cash increased to reach a total of 16% of the GDP of the eurozone in 2022 counting 342.56 million persons using the euro. According to Central Bank of India there were about 124.36 Billion banknotes and 122.99 Billion coins in circulation in 2021 in India. The Federal Reserve Bank published that there are 67.68 Billion banknotes in 2022 labeled in dollar and worth $2,750.27 Billion. For coins in the USA, there were about 28 Billion coins in circulation in 2016 but with 15 to 20 billion coins minted yearly according to the US Department of Treasury.

Based on the above numbers and by extrapolation according to population we reach a total of 842.6 Billion banknotes in circulation worldwide. To confirm our estimation we've checked with a second source that estimated at 576 Billion banknotes worldwide in 2018. Several central banks confirmed a growth rate of 12% to 16% per year of banknotes printing since 2018 this leads to count of notes between 1015 Billion and 1210 Billion banknotes according to this second source. This confirms our range of 842.6 Billion banknotes as a safe lower bound estimation with an average growth rate of 11.57% per year in the last 4 years.

For coins in circulation applying the same extrapolation leads us to ~1,507.7 Billion coins worldwide in 2022. We conclude that the globally the ratio of coins to banknotes is ≈ 1.79× although this ratio differs largely around the globe between ~1× in India to ~4.9× in EU.

What is important for us is the renewal rate of this cash mass. It's estimated that the renewal rate of banknotes is ~26.04% per year this leads to 219.42 Billion banknotes per year being printed to replace the worn notes taken out of circulation and to answer new demand.

Coins have a slower renewal rate. A circulating coin has an estimated 30 years lifespan or more and today the US Mint issued 15 billion coins in 2021 giving a renewal rate about 11.54% for the dollar and 2.52% per year for coins based on European Central Bank's data. Different countries might have larger increase ratio but we base our calculations on a renewal rate of ~7% and this leads to a global minting rate of 106 Billion coins per year. So the results are as follows:

Count(notes) ≈ 842.57 Billion notes [1a]

New(notes) ≈ 219.42 Billion notes/year [1b]

Count(coins) ≈ 1,507.7 Billion coins [1c]

New(coins) ≈ 106 Billion coins/year [1d]

Let's now estimate the energy consumption of [1b] and [1d].

Energy consumption of secure paper money printing is difficult to estimate precisely. Paper fabrication, printing, cutting, collating, counting, testing and binding is a complex and heavy industrial process (we will account for cash in transit later). But an easier approach that can give us the lower bound, is by estimating the energy consumption of industrial magasin manufacturing. We've calculated that printing 35,000 copies of a 96 pages magasin consumes about 37.2 KWh per page. This allows us to state that the printing [1b] can consume at least 8,163 TWh/year. About 83% of this energy is consumed in making the paper that goes through the press. Only 11.1% are needed to print, cut, collate. Since we are not taking into account the paper manufacturing but only the running operations of transforming the paper into banknote this reduces the energy value accordingly.

Energy(PrintNotes) ≈ 906 TWh/year [1e]

According to *"The United States Mint's 2011 Sustainability Report"* the US Mint's total energy consumption in 2011 was 192,906,111 KWh. This includes consumption of natural gas, diesel, liquefied petroleum, electricity and steam. In 2011, there were 8.7 billion coins minted by the US Mint. This gives us an energy cost per coin of ≈23.53 Wh/coin, and a total energy consumption for yearly minting worldwide today of about 2.49 TWh/year. This is excludes the metal mining and transport energy consumption and covers only minting process and transformation into central bank coin.

Energy(MintCoins) ≈ 2.5 TWh/year [1f]

In conclusion the total energy consumption of printing and minting cash is

Energy(Print&Mint) ≈ 908.6 TWh/year [1]

Note that on yearly bases, minting is using less energy than banknote printing because of a very large demand on banknotes compared to coins and because coins require no maintenance and are not recycled, there lifecycle virtually ends at production, while banknotes deteriorate quickly and are frequently renewed. We've excluded from the evaluation the energy consumption the mining of the metal coins and the manufacturing of paper notes according to our methodology. Finally we've also excluded the initial printing and minting of total cash in circulation and only evaluated the new cash entering into circulation yearly.

Energy of ATMs

We've computed and verified in our study that the total number of cash dispenser machines worldwide is estimated to be **4,823,564 ATMs**. This number can be reached based on country-by-country studies of the number of ATM machines per 100,000 individuals. We've verified this by double-checking central banks sources of 35 representative countries covering more than 5 billion persons on all continents and based on official central banks reports. Our calculations reached an average of 60.7 ATMs per 100,000 persons in the total serving the world's population of 7,939,000,000 people. This estimation takes into account the drop of ATMs usage in several countries worldwide.

For a small bank an ATM machine has an average daily power[18] of about 250W maximum according to a first source. We consider 230W per ATM on average for our calculations and evaluate that the energy consumption of world ATMs to be around 9.72 TWh/yr. A second source is Diebold, the ATM vendor estimates that an ATM has an average consumption of 1620 kWh/yr leading to 7.81 TWh/yr. We'll consider an average of 8.77 TWh/yr.

But in practice, ATMs are not used alone, they require two air conditioners and lighting (that can be in a branch or out of bound of a bank branch). A medium air conditioner consumes about 900W. Since running one air conditioner for 24/7 reduces its life span, two AC are used working[19] alternately to achieve full time coverage. By taking the average consumption of all ATMs and including only 1 AC unit this leads to a more realistic range of **46.8 TWh/yr** for all ATMs worldwide.

Energy(ATM) ≈ 47 TWh/yr [2a]

This estimation does not take into account: server side consumption, cash handling, or any maintenance interventions on ATMs. Therefore it can be seen as a minimal energy requirement to run world ATMs today.

Energy of Cash In Transit

Now let's assess the physical cash management energy consumption and focus on cash-in-transit (CIT), the physical transfer of banknotes, coins, credit cards and items of value from one location to another. The locations include cash centers and bank branches, ATM points, large retailers and other premises holding large amounts of cash, such as ticket vending machines and parking meters. Companies such as Loomis and Brinks are the main providers in this sector and are representative of the workload necessary.

Loomis has more than 200 cash processing centers equipped with technology to count, authenticate, and check the quality of banknotes and coins. We will ignore the verification and authentication machines consumption as an additional simplification of our model and focus only on the transit energy consumption. Loomis handles up to 50 million banknotes per day in the processing centers and has 6000 secure transport vehicles. Brinks has 1100 operations facilities, and a fleet of 13,300 vehicles. These vehicles consume significant amounts of energy. A diesel armoured car can be consuming ~3.3 kWh per kilometer. Note that kinetic energy is only 30% of the input energy required for the truck, the remaining is lost mainly in the exhaust. Estimates computed an average of ~35 litres of diesel every 100 km. One litre of diesel fuel has an energy of ~10 kWh. This confirms the estimate around 3.5 kWh/km.

CIT is a complex process with multiple steps. Cash vehicles can be transporting banknotes and coins from cash centres to banks, or from retailers to bank for instance. Almost all the fleet is used daily, CIT companies optimise the number of vehicles for these rotations without counting the energy cost for their maintenance as an additional simplification. In the majority of the time an additional step is added to the CIT process and a banalised vehicle belonging to the bank, drives along the armoured car thus almost doubling the number of vehicles involved but not to all the path of transit.

It is a very difficult task to estimate the number of armoured trucks for CIT worldwide. A good educated guess is to take into account the total

[18] These estimations ignores for now the energy consumption on the server-side of ATMs Manager by Diebold Nixdorf or NCR for instance

[19] Note that these AC units are not used in the bank branch itself by only dedicated to the ATM

number of banknotes in circulation worldwide, *see* [1a]. We've estimated that the velocity of banknotes is ≈ 1.5 ×, meaning that a banknote circulates and returns back to its starting point (ex. an ATM) 1.5 times per year.

Loomis fleet in the USA has 3000 vehicles (50% of their world fleet) and process 25 million banknotes per day in the US. This leads to an average capacity per CIT vehicle ~3,041,667 banknotes per year. Taken into consideration the velocity of banknotes and the total number of banknotes worldwide we estimate that there are about 6.03 million CIT vehicles in the world including a safe estimate of 1 bank car for each 2 armoured trucks counting 5.4 million trucks.

CIT(Vehicles) ≈ 6 million vehicles [2b]

When we take a moderate hypothesis that an armoured vehicle transports the cash for ~40 km per day over 220 days per year, and the banalised bank car accompanies the truck only for half of the path our estimations lead to a total cash-in-transit power of:

Energy(CIT) ≈ 166 TWh/yr [2c]

This figure does not account for processing centres and employees managing the cash and the distribution from central banks. This excludes also the energy consumption for the maintenance activities for these vehicles, so [E] should be considered as a minimum energy requirement for global CIT activity.

Energy of Cash at EPOS

Physical cash payments are private by nature and (without electronic traceability) are harder to count. In our research we've found that the share of cash transactions at an electronic POS is more frequent than the cash distribution by banks and even more frequent than electronic vicinity payments at shops. In Europe, cash transactions are on average about 68.1% of all vicinity payment transactions at POS[20]. Globally, les notes and coins represent more than 50% of transactions in most OECD countries. To verify this initial estimate we refer to the European Central Bank report that estimates the share of payment instruments used at the POS and P2P in terms of the volume (count) of transactions to be about 73% of all payment transactions including POS (and 48% of the transactions' value). We compute the average number of POS and P2P transactions per person per day, per country, to be about 1.14 cash Tx/day/person in Europe with large disparities between countries cash appetite: Greeks Italians and Portuguese make 1.6 cash Tx/day/person (compared to 0.5 for Dutch and Estonians). Based on the 1.6 figure as an average worldwide we extrapolate to world population, this leads to a 3.3 Trillion cash transactions on electronic point of sale per year. But since Europe has fewer cash transactions than the rest of the world the real number can be considerably higher.

PoS(CashTx) ≈ 3.3 Trillion Tx/yr [3a]

The total energy for a cash peer-to-peer transactions in the economy is more difficult to estimate since they are private by design, and not all of them are accounted for electronically. But it's important to account at least for the part that is processed by electronic point of sales desks because the cash management has a high cost effort for merchants too, not only banks. Today Visa alone serves 100 million merchants worldwide, a number in the rise largely driven by government initiatives to promote cashless payments. An educated guess of how many merchants accept cash payments only, can be the majority of the very small shops around the world that still do not accept card payments. Based on ECB estimates that 27% of vicinity payments are card transactions and 73% are cash at ePOS we can estimate that 370 million merchants accept cash using a PoS electronic system worldwide. If we consider that a PoS cash desk works 8 hours per day on average and uses as little energy as a PoS terminal about 111.6 W (*see references thereafter*) this leads to at least 72.75 TWh/yr for electronic cash desks at PoS working 220 days per year 8 hours per day and counting only 1 e-cash ePoS per merchant.[21]

Power(CashPayments) ≈ 72.8 TWh/yr [3b]

[20] Going from 88% in Malta to 77% in Germany to as low as 34% in Netherlands (59% in France)

[21] We will not account for cash transport by merchants between branches and by client since this could impact highly the results without being completely in scope for comparing with Bitcoin payments.

$$Power(ePosCashTx) \approx 22.03\ Wh/Tx \qquad [3c]$$

ENERGY OF CARD PAYMENTS

After estimating cardless PoS electronic cash management, we will estimate in this paragraph the energy consumption of card payment transactions. The card payment leader Visa has 4 data centers located in Central US, East US, UK, and Singapore, with a private communication network of 10 million route miles (400 times earth circle[22]). Although Visa keeps confidential the exact energy required by its data centers, it is possible to compute that Visa's data-centers require on average 305 MW per data center to operate [4c]. These calculations are based on Visa's annual report (*Visa Green Bond Report — July* 2021) stating that Visa's datacenter energy consumption stayed stable between 2017 and 2020 totalling 446 million kWh. This estimation leads to an energy consumption by Visa ≈ of 2.7 TWh/yr [4a]. Visa's market share can be estimated to be about 15% of total cards in the world. This can be obtained through Visa's declaration that is processes 3.8 Billion cards and we know that the total number of payment cards was 25.2 Billion cards in 2021. Now we can extrapolate [4a] and see that the total card schemes payments datacenter consumption is ≈ **17.72 TWh/yr** to operate all card payments worldwide.

$$Power(Schemes) \approx 17.72\ TWh/yr \qquad [4]$$

So based on Visa numbers we can extrapolate that the total payment cards generate 1.54 Trillion transactions per year (Tx/yr) [4d] or about 48,891 Tx/s moving USD 86.2 billion/yr. This leads to an average of 56 USD/Tx (in card payments) [4e].

As a reminder these transactions are not final, they are most of the time online authorisation requests to the Issuer on behalf of the Acquirer[23] and the payment will complete later with the collection, clearing and settlement transactions with central bank money. We will estimate the energy of these steps later in our study. As a result, card payment transactions (which is only an intermediary step of the end-to-end payment transaction) require globally about 11.49 Wh/Tx in energy to process through a card scheme like Visa or Mastercard for instance.

$$Energy(SchemeTx) \approx 11.49\ Wh/Tx \qquad [4a]$$

To complete the estimation, a card payment generally originates at a point of sale (POS) terminal in the case of vicinity payments[24]. We've estimated the global installed base of POS terminals to be about 207 million units in 2020. Then we've computed that the minimum POS energy consumption per transaction ≈ 0.9401 Wh/Tx. In a different and more accurate method, the average POS terminal energy consumption[25] is ≈ 111.66 W. If a terminal works 8 hours/day on average and is online 80% of working hours, we compute that the total POS terminals energy consumption is more precisely 54 TWh/yr for the 207 million terminals.

$$Power(POS) \approx 54\ TWh/yr \qquad [4b]$$

Based on [4] and [4b] we conclude that card payment transactions consumes 71.71 TWh/yr.

$$Energy(CardSchemes) \approx 71.71\ TWh/yr \qquad [5]$$

$$Energy(CardSchemeTx) \approx 46.51\ Wh/Tx \qquad [5a]$$

Note that the difference between electronic cash at PoS and ePoS is that one is only at cash desks energy consumption [3b] and the ePoS is for energy payment terminals accepting card payments [4b]. And these are 2 different hardware serving different means of payments at the point of sale.

[22] That is 5 096 800 Km of cables only between servers at the datacenter

[23] In card payments Issuer is the issuing bank of the card and the Acquirer is the bank of the merchant acquiring the payment on his behalf

[24] Since online payments originate in the same way as Bitcoin cryptopayments and e-commerce card payments they are kept out of the scope of the calculations.

[25] Source: *Energy Losses Due to Imperfect Payment Infrastructure and Payment Instruments* by Oleksandr Melnychenko, Oct 9, 2021

Energy of Banking Offices

We need to complete the estimation with the end-to-end workflow through banks and other cross financial institution actors such as clearinghouses and Swift like service providers. This does not include all the services provided by banks such as insurance, loans or trading, but focuses on the accounts and payments management services. The banking industry counts more than 25,000 banks around the world [6a]. Banks manage globally a high number of branches that also consume a large amount of energy to operate. Commercial bank branches according to International Monetary Fund, is about 14.145 branch per 100K individuals. Based on world population we can estimate that there are 1,122,972 bank branches [6b].

Count(Banks) ≈ 25,000	[6a]
Count(BankBranches) ≈ 1.123 Million	[6b]

Energy consumption of banking branches can be evaluated through the average number of kilowatt hours per square meter for a commercial building. According to the Department of Energy (DOE), this electrical energy is approximately 242.2 kWh/m².

Traditionally, bank branches have ranged[26] in size from 371.6m² to 557.4m². We have verified from an different source, a major French bank, that an average size bank can consume about 21% of its energy on offices and branches[27] and according to banks roadmaps of improving its energy efficiency of its offices and branches, it is targeting an average of 137.14 KWh/m² in 2024. This confirms the range and although banks worldwide are improving their carbon impact using their resources large disparities worldwide still remain between them. We will consider the average of 242.2 kWh/m² in 2022 worldwide. This leads to an energy consumption by total bank offices and branches worldwide of 151 TWh/yr, excluding for now IT services and banks data centres.

Power(BankBranches) ≈ 242.2 KWh/m²	[6c]
Power(BankBranches) ≈ 151.6 TWh/yr	[6]

Energy of Banking Commute

The number of employees working in banking can be estimated by extrapolation from representative countries where such statistics are available officially by central banks. Based on major American bank reports, central banks in China, India, Eurozone, and Japan we can estimate that 1,850 employees work per bank on average around the world. This leads to a total of 46,250,597 employees working in the banking sector worldwide [7a].

Given a list of about 100 top payment service providers worldwide, the average number of employees per PSP is about 12000. We have estimate the total number of employees working in payments industry to be more than 1.2 million employees worldwide ranging from ATM manufacturers, ePOS manufacturer to payment switches and processors etc.

Bankers ≈ 46.25 Million employees	[7a]
Payments ≈ 1.2 Million employees	[7b]

These estimations account for direct employees and ignore the somewhat significant numbers of external providers such as security and guards, CIT employees, consultants etc.

It is important to distinguish only the count of employees in [7a] working at least partly on payments and accounts management. We consider that employees working on security, fraud, maintenance, risks, marketing, accounting, compliance, and other cross streams or administrative functions fall in the same domain of payments and cash management since they are essential for these services. Although branch employees work also on loans and insurance sales but they are still essential in the cash management, distribution and management of credit cards, in addition to the execution of certain wire transfers and book keeping.

It's legitimate to reduce [7a] by subtracting banking functions solely related to loans, insurance and trading. Worldwide there are about 9.6 million

[26] We've based the calculation at 6000 square feet instead of 4000 to account for HQ and additional dependencies other than the bank branch offices for public.

[27] Source: Internal official information of one of 12 major French bank according to their program for improving energy efficiency.

traders, but not all of them work in banks. For example at the main large banks in France the Société Générale has 351 employees out of 133,000 employees worldwide, and 353 employees at the BNPP are traders out of the 193,319 total employees count. On average we can see that 0.22% of the total headcount is in trading which is negligible 103,365 traders working in banks. In another approach we can consider that about 25% of banking headquarters work on loans, insurance and trading, but almost 100% of branch employees fall into cash and payments operations at least part time. Therefore this demonstrates that the strictly non-banking and non-payments related employees can be considered to be at the margin and that [7b] can be reduced by a factor of 0.54% to focus only on employees concerned in the fundamental banking and payment services. As a safety measure we will ignore [7b] and reduce slightly [7a] to reach a lower bound of banks employees.

Count(BankEmployees) ≈ 46 Million [7c]

The average commute distance in transport per employee is known to be approximately 24.14 km one-way. This is an average distance between large city centres, suburbs and far country sites. According to major french bank internal numbers, commute energy is 57% due to car travels, 26% air travel, 17% train totalling 4400 Km/year per employee on average or 20 km/day confirming our estimate above.

An employee's transport energy consumption is 7 kWh per km per employee. Based on [7c] This leads to 3,420 TWh/yr for all employees' daily round trips considering 220 work days per year on average and ignoring air travel as a simplification of commute especially that banks policies are restricting nowadays travel by airplane to a minimum.

Power(Commute) ≈ 3420 TWh/yr [7]

Energy of Banking IT

Banks also possess data centres either in the vicinity internally or outsourced or on the cloud. The most precise way to calculate the energy consumption of a bank's data centre is to estimate the average number of servers used per bank. Based on our knowledge and our consultation with small and large banks we can estimate that each bank (small banks) has a minimum of 300 servers varying between large IBM mainframes to firewalls, database servers, routers, core banking and online banking, backup servers such, NAS storage etc. we will consider the lower bound of[28]:

Count(*BankServers*) ≈ 300 servers/bank [8a]

In terms of annual energy usage, a two-socket server may use approximately 1,314 kWh/yr (which is simply just powering it on) to about 2,600 kWh/yr [8e]. IBM servers' idle energy usage is related to the number of Central Processing Unit (CPU) sockets and has remained static since 2007 at 365W for two socket servers (Shehabi et al, 2016; Shehabi et al, 2018). But in reality a server in a data center facility requires more power. A more accurate estimate might come from calculating how many servers could be used with a given energy capacity. If a similar high tier data center has an 850 MW capacity, and each rack was using 25 kW of power, that institution could operate 1,768,000 servers. This leads to a minimum required energy of 0,481 kW/server that then consumes 4,212 kWh/yr [8b]

To count the total number of servers used in banking we proceed as follows in a different approach to validate our estimations. While Amazon and Alphabet devote 12% and 20% of their operating costs respectively to IT, banks are devoting 29% of their operating costs to IT spending. This informs us that banks' IT budgets are 2,42 × times higher than GAFA and other industries [8c].

There are 100 million servers that are currently being used all around the world. A substantial number of these servers are owned by Google and Microsoft. In total, we've estimated that bank data centres use 7,500,000 servers [8d], 7.5% of all servers worldwide which is a logical minimum figure based on [8c].

[28] This is the average for small banks, so in reality the numbers are at much higher

Let's adopt a different approach. We have verified with a major French banks that it possess 2 datacenters consuming 1250 KW each. Leading to 21.9 GWh/year. Using [6a] this extrapolates to 547.5 TWh/year for all banks datacenters. But not all banks are major banks. For instance in France the ratio is 3.13% major banks and this gives us about 783 major banks worldwide out of the 25000 banks. This allows us to estimate that major banks consume about 17.15 TWh/year on their datacenters. While smaller banks consumes much less but are much more in numbers. Based on [8d] and [8b] we compute that the minimum bank data centres energy consumption is ≈ 31.6 TWh/yr with 85 MW per datacenter on average for all banks worldwide. Major banks consumes about 55% of this energy spent.

Power(BankDatacenters) ≈ 31.6 TWh/yr [8]

Energy of Inter-Banking

Inter-banking communications using financial messages for wire transfers clearing and settlement are also required to complete the study. Swift operates three data centers - one in Zoeterwoude, Netherlands; another in Culpeper, Virginia, United States; and a third in Thurgau, Switzerland. It also has a Command and Control center in Hong Kong. Not all banks are connected to Swift but only 11,000 banks. We can conclude from the above sources that Swift represents 44% of this use, based on [6a].

Using [4c] we estimate a minimum of 21.29 TWh/yr of the energy consumption of Swift-like messages in data centres alone.

Power(FinDataCenters) ≈ 21.3 TWh/yr [9]

Clearing and settlement mechanisms (CSM) are used by banks to complete payment transactions like EBA in Europe and STET in France for instance. As a reminder sending a simple email on the internet requires 25 Wh of energy [10a]. As a sample, STET, the French CSM processed in 2020: 16.74 billion transactions per year [10b]. The total card volumes[29] according to Banque de France is 49% of total payment transactions. Based on [4d] this means that the total number of world payments is 3.146 trillion Tx/yr, including card and non-card payments, such as wire transfers and direct debits, requiring clearing in most cases.

Count(PaymtTx) ≈ 3.146 Trillion Tx/yr [10c]

CSM messages are cleared in batch file mode in general, yet now they are becoming instant payment transactions like Faster Payments in UK and SEPA SCTInst Scheme in Eurozone. We can either use a methodology of estimating energy consumption of encryption and transfer of large data transfers between banks and CSM or use a simplified approach using individual level transactions. Based on [10c] and both [4a] and [10a], we can evaluate the lower and upper bounds of energy consumption for CSM messages to be between 36.2 TWh/yr and 79 TWh/yr. It's safe to consider the average[30] equal to 57.4 TWh/yr. The rationale of this approximation is that certainly a large clearing batch file consumes hugely more than a single card authorisation call as found for a single Visa transaction [4a], Power(CSM) > 36.2 TWh/yr. And it's since the transactions for CSM are grouped by thousands, to tens of thousands each transaction will consume much less than a 1MB email as in [10a] so the Power(CSM) < 79 TWh/yr. So the average is clearly near the real value.

Power(CSM) ≈ 57.4 TWh/yr [10]

Finally, banking employees use personal computers, as well as banking software relying on backend servers usually on the cloud. On average, there are 20 deployed computers per server leading to 2 312 530 servers in the backend for banking as well as 46 million personal computers for bank employees (*See* [7c])

Using [8c] and [11a] this translates into 6.01 TWh/yr for total backend servers and cloud energy used by banks for AWS, Azure and other SAP like SaaS. In

[29] Number of transactions not amounts

[30] As a reminder a single payment clearing transaction requires several API calls between small bank to the primary bank to CSM then to the central bank and back to the bank and the payer and the payees accounts, batch file calls also uses streaming of files over the internet which consumes much more energy than a simple and small single transaction authorisation the quantity of data in EMV norm of card payments contains much less data then a batch grouping tens of thousands of transactions per hours or day. So it's a moderate estimation to only use [10a] and [4a] instead of *n* times for *n* API calls energy costs. Here we used an approximation because such energy consumption differs very highly between banks.

addition, desktop computer consumes about 600 kWh/yr [11c] leading to 27.60 TWh/yr.

Count(BankITServers) ≈ 2.3 million	[11a]
Count(BankPC) ≈ 46 million	[11b]
Power(FrontToBack) ≈ 33.58 TWh/yr	[11]

Results For Classical Payments

Finally, we have completed the evaluation of the energy consumption for all the classical monetary and payment systems. In conclusion, we can estimate that the total energy consumption is the sum of intermediary results in TWh/yr.

Energy(*ClassicSystem*) ≈ 4981 TWh/yr	[12]

Given the large differences in scale between [1][6][7] and the other energy cost centres, it is important to clarify the legitimacy of including them. As a reminder, old telephone center buildings and their telephone booths around the world got transformed through telecom industrialisation and were eventually replaced by electronic telecom switches for efficiency, scalability and better services. The same way can be applied to the services domains that Bitcoin aims to cover. Note also that [1][6][7] can be considered a lower bound since we didn't take into account any central banks nor all the additional registered electronic money issuers and payment service providers data centres (such as Stripe, or PayPal for instance).

Next we will evaluate Bitcoin PoW energy.

Energy of Bitcoin

Let's now analyse the Bitcoin blockchain PoW energy consumption, excluding its layer 2 for Bitcoin Lightning for now. The most referenced assessment work is Cambridge Bitcoin Electricity Consumption Index (CBECI). According to Cambridge, Bitcoin power is supposed to be equal to 144.82 TWh/yr [13] with a lower bound of 53.29 TWh/yr and a higher bound of 356.83 kWh/yr. This large range seems more as a guess[31] work by Cambridge than a precise evaluation and these numbers are continuously used to criticise the PoW of Bitcoin. Cambridge acknowledges using different hypothesis of electricity prices for profitability estimations and *"uses simplistic weighting of profitable hardware"* yet Cambridge is aware that *"assuming that all profitable equipment is equally distributed among miners is unrealistic given that not all hardware is produced in equal quantities and readily available"*. So there's plenty of room for improvement on their work and that's what we will undertake in this paper with a completely different methodology.

The best and most scientifically precise method is to count Bitcoin miner nodes and hardware units and then based on the required computing power (PoW difficulty) of the installed base of miner units, we can precisely estimate the kWh actually used by each mining unit available on the Blockchain. Today 100% of mining units are a special hardware model called ASIC (Application-Specific Integrated Circuit). Therefore, we can exclude today Bitcoin mining through CPU or GPU since they are out of the network or extremely marginal.[32]

After China's mining ban, Bitcoin Mining Map shows that USA became recently the leading Bitcoin mining country with 35.4% of global hash rate power of the Blockchain. It's important to escape listing all currently in use ASIC hardware according to their profitability. This approach requires to cater for electricity prices and we do not need to use this inaccurate path in our research. A better path is simply hardware efficiency: that is Watt consumed per Terahash and the release dates of each model. Non profitable miner units are most probably today switched off, because by definition the miner will be literally loosing money if they switch them on, depending on electricity costs. That said, we've verified with industrial miners that they are still using certain older ASIC models considered today non profitable based on average electricity price. That's possible because certain industrial miners negotiated very low cost of energy rendering profitable older models.

[31] Cambridge Index speaks of constructing a *"best-guess"*

[32] CPU and GPU mining represent considerably less than 0.000000001% of mining power and they are completely inefficient and not used actively in mining. We will only consider CPU and GPU mining in our research to compile initial mining data in the first 5 to 6 years of PoW mining

Let's call i the index of a mining unit model m_i out of N_t models at time t. We call the Power Efficiency π_i of a mining unit m_i, the amount of power required to reach a rate of 1 tera-hash.

$$\pi_i = \frac{Power(m_i)}{Hashrate(m_i)} \text{ (in W per TH)} \qquad [14]$$

Let's start by building the mathematical model and theory of Bitcoin PoW mining. Let at any point in time t:

$M_t = \{m_0, m_1, \ldots, m_{N_t}\}$ $|M| = N_t$ *miner models*

Where M is the set of miner unit model m_i and N_t is the total count of models available at any point of time t since the mining started in 2009 until today in 2022.

Let $R_t = \{r_0, r_1, \ldots, r_n\}$ $|R| = |M|$

Such that $\forall m \in M,\ f : M \to R$ give us the release date and allows us to determine the age α_i of the mining unit in order to determine later its market share of the hash power and its energy consumption. Give a time t, we can model all miners attributes using this approach:

$$Miners(t) \to \begin{cases} M_{model} = \{m_0, m_1, \ldots, m_{N_t}\} \\ M_{release} = \{r_0, r_1, \ldots, r_{N_t}\} \\ M_{hash} = \{h_0, h_1, \ldots, h_{N_t}\} \\ M_{power} = \{p_0, p_1, \ldots, p_{N_t}\} \\ M_{efficiency} = \{\pi_0, \pi_1, \ldots, \pi_{N_t}\} \\ M_{count} = \{C_0(t), C_1(t), \ldots, C_{N_t}(t)\} \end{cases}$$

For each miner we consider the set $m_i \to \{r_i, \alpha_i, h_i, p_i, \pi_i, C_i(t)\}$ where $C_i(t)$ is the count of the model m_i at a given time t, online and contributing to the Bitcoin Blockchain PoW. ASIC miners life expectancy is between 3 to 5 years and we've verified this information with the mining industry directly. So in our research we've accounted for N_{max} = 91 miner models with a release date between July 2014 and May 2022 ($\alpha_{max} \leq 5$ years period). Other older models can be safely considered out of the Bitcoin network today (or not impacting the results).

$$Miners \to \begin{cases} N_{max} = 91\, models \\ r_i \in [r_{min}, r_{max}] = [2014.07, 2022.03] \\ \alpha_i = t - r_i, \alpha_{max} \approx 60\, months \\ h_i \to TH/S \\ p_i \to Watt \\ \pi_i \to Watt/TH \\ C_{m_i}(r_{min}) = C_{m_i}(r_{max}) \approx 0, \forall i \in [1, 91] \end{cases}$$

The most precise way to evaluate the Bitcoin PoW energy consumption is to calculate the most accurate count $C_i(t)$ of installed units for each model over time. But since sales data are not available and the Blockchain does not register the mining model this approach seems impossible. Yet we've found that the increase of the total hash rate ΔH_t of Bitcoin can give us a precise indicator of the growth of the hash power of the total installed miners: At any point t in time, $H(t) = \sum_{i=0}^{N_t} h_i C_i(t)$. [15] where $H(t)$ is the hash rate available on Bitcoin at time t. This data can be reliably read from Bitcoin Blockchain in near real time. The hashing power is estimated from the number of blocks being mined in the last 24h and the current block difficulty. More specifically, given the average time T between mined blocks and a difficulty D on Bitcoin PoW, the estimated hash rate per second H is given by the formula $H(t) = 2^{32} \times \frac{D}{T}$. Where T ≈ 10 min but in the calculation of hash rate the real value on the blockchain are used and that can be for example less than 10 min. Therefore the hash rate although calculated, is extremely precise for our work up to 10 minutes periods, while we are working on monthly rates and numbers over 13.3 years period.

The hashing Difficulty is a measure of how difficult it is to mine a Bitcoin block, or in more technical terms, to find a hash below a given target. A high difficulty means that it will take more computing power to mine the same number of blocks, making the network more secure against attacks. The difficulty adjustment is directly related to the total mining power in the Total Hash Rate (TH/s). When the Bitcoin hash rate increases or decreases by $\Delta H(t)$ this is due to the fact that the installed hardware park increased in the total count of mining units across all models m_i. This delta increase or decrease will be distributed among older and newer hardware released.

These considerations lead to one equation with up to 91 or more variables making it impossible to compute each $C_i(t)$. Yet the total hash rate is distributed over the available models N_t. This fact can lead us to a first average calculation but we can achieve a much better evaluation. We note that for $t \leq July$ 2014 all old miners are not online anymore, therefore it's allowed to estimate them as one unified virtual model. Let's call m_0 the virtual miner hardware starting since the $r_0 = r_{min} = 2009.02$ *(month 1 of Bitcoin going online)*. Since this virtual ASIC miner can be considered alone in the market until $r_1 = 2014.07$ *(month 68)*, it's now easy to compute the count of m_0 for all the period $C_0(t) \forall t \in [1,68]$ using:

$$C_0(t) = \frac{H(t)}{h_0} \forall t \in [1,68] \textit{ total months } [16]$$

In the example above we see that in this model the virtual m_0 with its 0.18 *TH/s* is allowed to have a count of units less than one (*until Feb 2011*) since it simulates all older models: 2 ASIC models, some GPU and CPU models. And since m_0 and all these models combined are no longer online, it's still a very accurate start to build on for the next released models.

So m_0 equations become as follows:

$$m_0 \rightarrow \begin{cases} N_{max} = 1\, model \\ r_0 = r_{min} \in [2009.02, 2019.05] \\ \alpha_{max} \approx 120\, months \\ h_0 = 0.18TH/s \\ p_0 = 360W \\ \pi_0 = 2000W/TH \\ C_0(t) = \frac{H(t)}{h_0} \\ \forall t \in [1,160]\ months \end{cases}$$

Note that exceptionally the maximum age of m_0 is 10 years instead of 5 years. It is legitimate to allow for new models to replace it in the market and because the last miner issued more than 5 years ago is the Bitmain AntMiner S1 with 0.18TH/s model and released in Nov, 2013, this model is used as m_0 unifying all older ASIC, GPU and CPU inefficient hardware. At the same time, Bitcoin total hash rate was millions of times smaller growing from H(1)= 0.0000044 TH/s in 2009.02 to H(58) = 2,559 TH/s in 2013.11, an increase of 581 million folds in about 4 years. This confirms our approach for m_0 and its 0.18TH/s capacity as the unified model of all older hardware no longer online since 2019.05.

For example, the virtual number of miner units is:

$$C_0(20) = \frac{H(20)}{h_0} = \frac{0.00417\, TH/s}{0{,}18\, TH/s} = 0.0232 \textit{ miner units}$$

$$C_0(61) = \frac{H(61)}{h_0} = \frac{15{,}943\, TH/s}{0{,}18\, TH/s} = 88{,}570 \textit{ miner units}[33]$$

Once a new miner model m_1 is released to the market at least 1 to 3 months are required for it to be part of the Blockchain hashing power, and will follow a growth rate replacing gradually m_0 market share and hash rate until it leaves the installed park of miners and goes offline ~60 months (5 years) later. Using its life time, it will share the hash power with newer models m_i launched after its market entry.

Since the sales are not known and the average distribution is not precise enough, we've demonstrated that Bitcoin hash rate variation ΔH_t is directly proportional to the sum of all $\Delta C_m(t)$ that corresponds to the total miners installed and taking into account new hardware, minus older miners gone offline. This leads to $\Delta H_t = H_t - H_{t-1}, \forall t \in [1,160]$ *months* being directly proportional to: ΔCount(miners at *t):*

$$\sum_{i=0}^{N_t} C_i(t) - \sum_{i=0}^{N_t} C_i(t-1) = \sum_{i=0}^{N_t} \Delta C_i(t) \Rightarrow$$

$$\Delta H_t = \sum_{i=0}^{N_t} h_i \times \Delta C_i(t)$$

And the total count of mining units being at a given time = $\sum_{i=0}^{N_t} C_i(t)$ *miners*

Since h_i and p_i are given by the manufacturers for all models, we need to find the most accurate approach

[33] At this stage this is a virtual model count. Miners here are not nodes. Nodes are often pools of mining hardware of ASIC models. At month 61 we can estimate that 88,570 miner units were online actively participating in PoW on Bitcoin nonstop.

to calculate $\Delta C_m(t)$ for each one of all N_t miner models at a given[34] time t.

If the distribution of new hardware to the market is made evenly *(which is not)* and before we apply additional improvements to this method, it's possible to solve an approximation of the many variable equations using the series based on m_0 information :

$$C_i(t) = C_{i-1}(t) + \frac{\Delta H_i}{N_t h_i} \text{ giving us } \Delta C_i(t) = \frac{\Delta H_i}{N_t h_i} \quad [17]$$

Let's now find a very accurate solution for the equation. For m_0, the $C_0(t)$ is determined 100% accurately thanks to blockchain data until the release date of m_1 at $r_1 = 68$. Until $\alpha_0 = 68$, m_0 is the only mining virtual model in the market. This will allow us to compute a first (but unsatisfying) estimation of all mining units over time. In order to improve this model to the maximum extent, we need to find a precise distribution model of miner units installation usage and gone offline. In economy and in physics new products entering a market follow globally the normal[35] distribution law in general. We will not undergo a full demonstration here, but let's state that this has been verified for many products in logistics and here's a quick logical verification for the miners products:

- Once a new mining unit is released, it takes a certain delay to be pre-sold, sold, manufactured, stored, shipped and delivered, thus initiating the start of the bell shape with an exponential growth. Mining market information shows a delay of 1 to 3 months to start a growth penetration phase of the product.

- Then once it becomes largely available in the market, it grows relatively exponentially in sales and installation before its growth rate decelerates and then gets limited due to 2 factors: market saturation, price to power efficiency (π_i), and new better models entering the competition limiting the demand on the previous models.

- Once the interaction of several competing models occur, the previous model decelerates its growth to halt at a maximum marketshare then the curve starts reversing while the new models grow exponentially and the older model starts getting out of market following the reverse process is sensibly symmetric, until the same process occurs in loops also for the newer models.

The maximum age on average of any m_i is 5 years of full-time run thus giving us a knowledge of the Gauss curve span. This important piece of information is crucial to solve the complex equations. A normal distribution curve requires 2 variables to be modelled the:

$$\gamma_i(t) = \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu_i}{\sigma_i}\right)^2} \quad [18]$$

Where $\pi = 3.14159265359...$ and e is another mathematical constant called Euler's number[36] $e = 2.71828\ldots$ then σ is the standard deviation and μ is the mean value of the distribution (median). Since we know that a miner age $\alpha_{max} \approx 60$ months, we can consider that $\mu_i \approx 30$ months on average for any miner for Bitcoin.

We still need to determine the σ_i. The standard deviation is a measure of the dispersion of a set of miner model m_i. A low standard deviation indicates that the values tend to be close to the mean $\mu_i = 30$ *months*, while a high standard deviation indicates that the values are spread out over a wider range. Since we are looking for an $\alpha_{max} \approx 60$ *months* as the wide spread of the normal curve, this solves to a $\sigma_i \approx 6.5\,months\ \forall i > 0$. The interpretation of this value is that between $-\sigma_i$ and $+\sigma_i$, a period of 13 months, 68.2% of the total model m_i sales are in production and online on the blockchain. And between $-2\sigma_i$ and $+2\sigma_i$ (26 months period) 95.4% are in production. This leaves a long tail outside the range $\pm 2\sigma_i$ (more than 2 standard deviations) for entering the market and exiting the market on the borders of the curve, and this was verified with mining centres still using almost 5 years old hardware. Given in our model $\sigma_i = 6.5\,months$ and $\mu_i = 30$ *months* we can now compute the percentage each product sales and installation. We need now to correlate the product penetration rate with different

---

[34] Overclocking miners will increase the hash rate and increase the consumption. We did not take this into account in the model since the Power Efficiency remains relatively the same thus not affecting the total energy consumption of Bitcoin in total but only requiring marginal less hardware consuming marginally a little more power but ending with an equivalent energy consumption globally.

[35] Also called Laplace-Gauss law, Gauss Law or simply bell shape curve

[36] Called Euler's number

competing models and determine the most precise count of each model in time, that is to solve $C_i(t), \forall i \in [1, N_t], \forall t \in [1,160]$ *months*.

Since the $\Delta H_t = \sum_{i=0}^{N_t} h_i \times \Delta C_i(t)$ and since we know the value of $C_0(t)\ \forall t \in [1,68]$, it's possible to compute one by one the series $C_i(t)$ based on $C_{i-1}(t)$ using the proportion of each model sales given by $\gamma_i(t)$. We've demonstrated that the solution for this complex equation is in [19] below.

$$H(t) = C_0(t)h_0 + \ldots + C_i(t)h_i + \ldots + C_N(t)h_N \Rightarrow$$

$$H(t) = \sum_{i=0}^{N_t} C_i(t)h_i$$

$$\textit{Verifying } C_i(t) = \frac{H(t)}{h_i} \times \frac{\gamma_i(t)}{\sum_{j=0}^{N_t}\gamma_j(t)}\ \forall i \in [0,N_t] \Rightarrow$$

$$H(t) = \sum_{i=0}^{N_t} \frac{H(t)\times\gamma_i(t)}{h_i \times \sum_{j=0}^{N_t}\gamma_j(t)} \times h_i\ \textit{, since } \sum_{j=0}^{N_t}\gamma_j(t) = 1$$

$$\Rightarrow H(t) = H(t) \times \sum_{i=0}^{N_t}\gamma_i(t)\ ,$$

Which is true since $\sum_{i=0}^{N_t}\gamma_i(t) = 1$. *And that demonstrates that*

$$C_i(t) = \frac{H(t)\times\gamma_i(t)}{h_i}\ \forall i \in [0,N_t] \Rightarrow \blacksquare$$

$$m_i \rightarrow \begin{cases} C_i(t) = \dfrac{H(t)}{h_i\sigma_i\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu_i}{\sigma_i}\right)^2} \\ \forall i \in [0, N_t], \forall t \in [1, 160] \\ \sigma_i = 6.5\, months \\ \mu_i = 30\, months \end{cases} \qquad [19]$$

This important m_i equation allows for an accurate description of Bitcoin energy consumption based on the precise number of miner units for all miner models. The equation results are confirmed for all calculations up to 0.00000001 precision at any point in time t during the 160 months period.

Bitcoin Blockchain Explorer indicates that the current miners network hash rate ≈ 204 million tera-hashes per second[37]. And we can read on the blockchain all H(t) values daily since the genesis block.

Now we can finally compute the energy consumption of Bitcoin PoW using :

$$P(t) = \sum_{i=0}^{N_t} p_i C_i(t) \qquad [20]$$

Where *P(t)* is the electrical power of Bitcoin's PoW in *Watt* at time *t*. We were able to compute the number of each installed miner units during 160 months for each m_i model. Here are the values today at t = 160 *months*.

$$H(160) \approx 204 \times 10^{18} H/s \qquad [21]$$

$$TotalCount_M(160) = 3{,}990{,}685\ \textit{miners} \qquad [22]$$

$$P_{Bitcoin}(160) \approx 88.95 TWh/yr \pm \epsilon \qquad [23]$$

$$\textit{Cumulative miner models count} = 92\ \textit{models} \qquad [24]$$

$$\textit{Current miner models online today} = 80\ \textit{models} \qquad [25]$$

$$\pi_M = 49.7 W/TH\ \textit{on average of current miners} \qquad [26]$$

To see the evolution of PoW Power Efficiency over time see π_{PoW} graph in the diagram [D5] above.

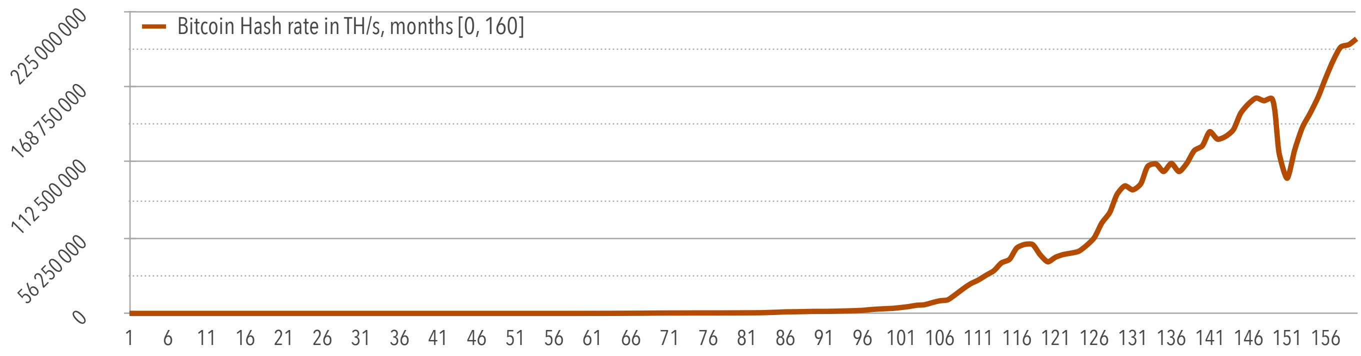
The importance of the count of hardware per model is that it allowed us to calculate that there are ≈ 4 million miner units of the different models today worldwide grouped in the 15,636 reachable Bitcoin nodes. Note that our approach do not require any mapping per country nor uses electricity pricing directly or indirectly in anyway.

Since the power of a hardware is determined by the manufacturer and verified by the mining community we can consider its value precise with a very low error margin (less than 2%). The error margin of bitcoin energy consumption can originate from 2 sources:

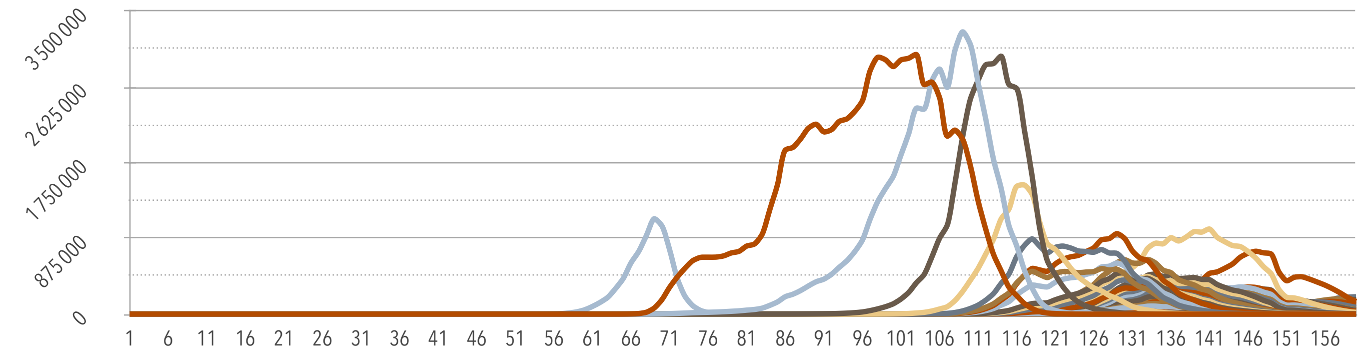
- Our $C_i(t)$ estimation and the precision of the p_i *in Watts* provided by the manufacturer[38]. In our

[37] That is 204,000,000,000,000,000,000 cryptographic hashes/second

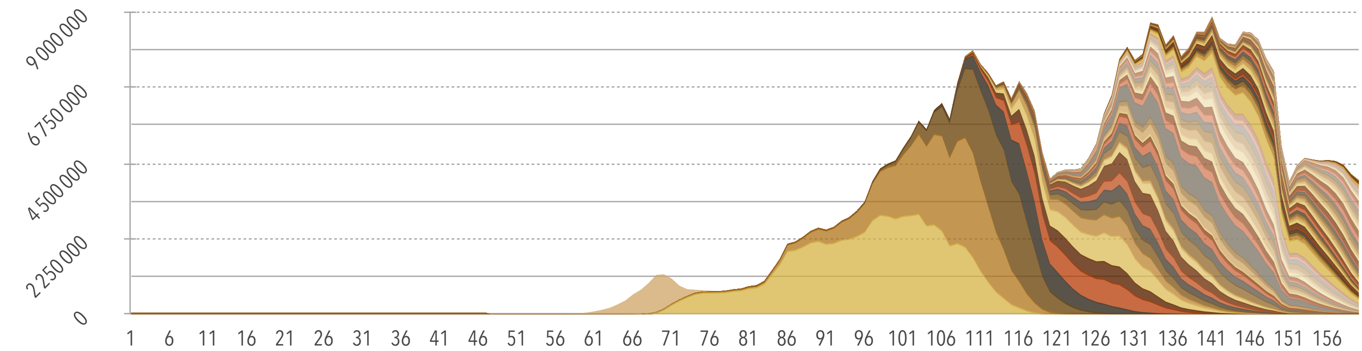
[38] Note that overclocking ASIC miners may improve the hash rate capability and increase the required energy consumption value of the miner unit but the power efficiency remains relatively constant thus not affecting the final result especially that all us bound by the Bitcoin total hash rate. So this can produce a variation less then the error margins of our $C_i(t)$



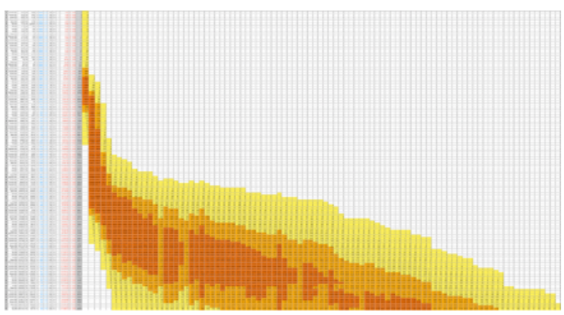
[D1] *Bitcoin hash rate in according to the Blockchain data*



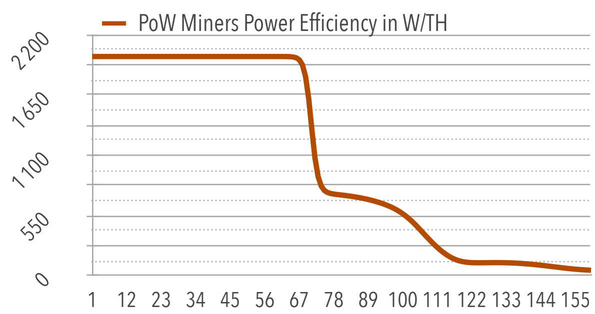
[D2] *Count* $C_i(t)$ *of each one of the 92 ASIC miner models contributing to PoW over* [0, 160] *months*



[D3] *Total count of mining units over time (accumulation of the count for the 92 ASIC miner models) over 160 months*



[D4] *Calculation of* $C_i(t)$*: Count of miners for 92 ASIC models (left to right columns) in* [0, 160] *months (top down rows)*

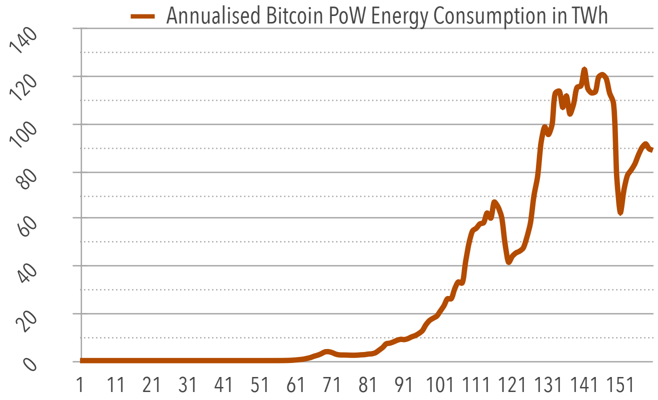


[D5] *Evolution of PoW total miners Power Efficiency* π_i *of all models overs 160 months See* [26] approach we do not need to consider that the hardware up time rate per year (~ 99.9%) since we've computed the exact real ASIC miners uptime consumption.

- Varying the values of σ_i and μ_i generate results deviating by $\epsilon < 5\,\%$ comforting the precision of our calculations. In contrast, the error margins of Cambridge index are very large with $\epsilon_{CBECI} \in [-63.2\,\%, 146.4\%]$.

This updates our [23] to:

$P_{Bitcoin}(today) = 88.95TWh/yr (\epsilon < 5\%)$ **[23]**



[D7] *Energy consumption of Bitcoin PoW between* [0, 160] *months*

Note also that not all the 92 ASIC miner models used are solely for Bitcoin mining many of them are not that efficient for Bitcoin and are mostly used to mine other cryptocurrencies. Based on this principle alone we can see that the [23] is actually an upper bound. And if we take this argument into account, miners with higher π_i will be more used in mining Bitcoin and this will improve the actual Bitcoin energy consumption further.

Hypothetically if all mining units were replaced by the most efficient ASIC (having the lowest π_i possible today), Bitcoin energy consumption would drop to $\pi_i = 29.5W/TH$ instead of [26]. This leads to the same H(*t*) work with a large drop of Bitcoin energy consumption by 40% to only 52.8TWh/yr. So it's possible to run all Bitcoin network with 52.8TWh/yr today without triggering the hash rate adjustment the hash rate required for PoW. Note that this is not an actual lower bound but minimum required energy today and the hardware uses actually 88.95 TWh/yr to do the same work[39].

Minimum possible energy consumption today
$P_{Bitcoin}(minimum) = 52.8TWh/yr$ **[23a]**

Comparing at Transaction Level

We can conclude that the cryptopayment system of Bitcoin PoW consumes at least ~56 times less energy than the classical electronic monetary and payment system.

$E_{classic} \approx 56 \times E_{Bitcoin}$ **[27]**

Let's compare now the *work* and *power* of the 2 systems. It's not enough to compare only the total energy usage of both system. We have to compare now the *energy efficiency* per transaction level and the quantity of *work* and *power* involved in these 2 systems.

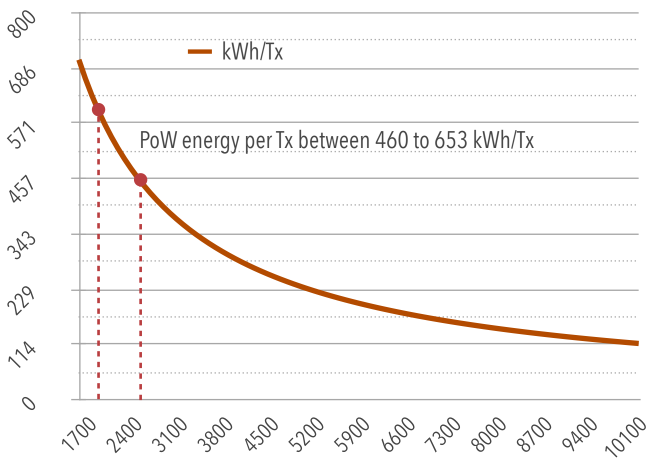
Let's start by comparing the energy consumption at a single transaction level. For Bitcoin, the current block size is between 1 MB to 1.52 MB and hosts today about 2,591 Tx per block. A Bitcoin block now have a theoretical maximum size of 4 MB and a more realistic maximum size of 2 MB[40]. The exact size depends on the types of transactions. So the maximum capacity of bulk processing per block can be about ~10,380 Tx/block. This result is obtained using a variable size of a bitcoin transaction between 303 and 454 KB/Tx (from median to average). We've computed that Bitcoin can process up to 544,879,300 Tx/yr and currently is processing about 136.22 million Tx/year (operating at 24% of its capacity). So on average a single Bitcoin Tx requires today 653 kWh/Tx but can be executed in 115kWh/yr with more adoption of Bitcoin in cryptopayments.

[39] Note also that commute energy consumption of employees running the ~ 15,636 nodes is negligible compared to 46 million banks employees without counting the very high number payment service providers employees. In addition most of the nodes manager work is done remotely in monitoring and remote maintenance. We didn't include physical maintenance of banking and Bitcoin since it's in the disadvantage of the classical payments system.

[40] This difference is due to the fact that Bitcoin uses now a maximum "weight limit" of a block. Block weight is a measure of the size of a block, measured in weight units. The Bitcoin protocol limits blocks to 4 million weight units, restricting the number of transactions a miner can include in a block. Four million weight units is equivalent to 4MB of data, meaning the maximum size for a block is now 4MB.

$Count_{current}(BitcoinTx) \approx 136.22 \times 10^6 Tx/yr$	**[29]**
$Count_{max}(BitcoinTx) \approx 544.88 \times 10^6 Tx/yr$	[30]
$Peak_{real}(BitcoinCapacity) \approx 4.32 Tx/s$	[31]
$Peak_{max}(BitcoinCapacity) \approx 17.3 Tx/s$	[32]
$Power_{avg}(1Tx) \approx 653 kWh/Tx$	**[33]**
$Power_{min}(1Tx) \approx 115 kWh/Tx$	**[34]**
$E_{PoW}(160) \approx$ 1,180,220 kWh/block (today)	[33a]
$P_{PoW}(160) \approx 10.154 GW$	[33b]

Note that [33a] is obtained through the current total power of PoW 10.154 GW in [33b] and a currently low Median Block Confirmation Time = 6.974 minutes/block instead of 10 minutes/block.



[D7a] *Current energy consumption of a single Bitcoin transaction using PoW in kWh per Tx versus number of Tx per block in* [1700, 10100] *Tx/block*

The minimum power per Bitcoin transaction can occur when the maximum capacity of a block is used. Note that [33] and [34] cannot be extrapolated to larger volumes since Bitcoin transactions are grouped in blocks and a single block can contain up to ~10K Tx. We will see below the method that Bitcoin can scale above this block limit using Bitcoin layer 2 called the Lightning Network.

The current monetary payment system is at least 5,775 times bigger than Bitcoin in terms of payment transaction volumes [30] and [10c], and had 60 years more time to get optimised and to scale yet consumes ~56 times more energy than Bitcoin PoW does.

Comparing energy efficiency per transaction of the two competing systems is not a direct calculation of the total transactions count per year over the total energy consumption. Although this might seem logical to compare energy on a single transaction, doing so is incomplete because it would be comparing apples to oranges. A bitcoin transaction and a classical system transaction do not have the same number of steps, pre-requisites and most importantly do not get settled at the same duration. A Bitcoin transaction gets settled in near real time within 10 minutes on average[41]. While in a classical payments transaction the settlement occurs in about 1 to 5 business days *i.e. up to* 7 days[42]. Most of local transactions are usually settled in T+2 which is in 2 days. Cross border payments settle slower due to additional barriers. **Classic payments can be settled up 1008 times slower than a Bitcoin transaction**. This is the case for cross-border payments for example. They are ≈ 2% of total payments worldwide but increasing extremely fast due to massive adoption of online payments and mobile payments with global marketplaces and immigration working force. But in the larger case, we can consider that the settlement duration of classical payment transaction is on average 2 days. **A classic payment transaction is on average 288 times slower than a Bitcoin transaction**. [35]

In physics power is the energy consumed in a given duration, and the work is a form of change in energy that also when divided by time gives power. So let's compare *work* done by Bitcoin and the *work* done by the classical electronic payment and banking system. Based on [0]

The classical electronic system consumes at least 1.58 kWh/Tx on average (*see* [12] and [10c]) but completes the *work* in ~48 hours on average. Bitcoin consumes between 115kWh/Tx up to 653 kWh/Tx currently and finishes the transactions in ~10 minutes on average (*currently in* 418.44 *seconds*).

[41] The current Median Confirmation Time on Bitcoin Blockcain has recently dropped to ~7 minutes. Bitcoin PoW mining difficulty is adjusted every 2016 blocks (every 2 weeks approximately) so that the average time between each block remains 10 minutes.

[42] Swift GPI hasn't been adopted yet but will allow in the future for faster cross border transactions within minutes too. Central Bank Digital currency experimentation (Donbar Project by BIS) tested a different approach using multi-CBDC between central banks directly. But these systems are not yet in production. See also Swift *How long do wire transfers take?*

It's also important to understand the meaning of the average 1.58 kWh/Tx for the classical system. This average is based on all 3.146 Trillion Tx/yr that the banking and payments system processes while consuming 4981 TWh/yr (*see* [10c] *and* [12]). And is computed as the lower bound estimation after several simplifications. It's clear that the banking system as a whole can sometimes consume much more or much less energy per transaction depending on the different nature of the payment act: cross border, card, or non-card, instant payment, cash transaction, vicinity or online transactions. Similarly it's important to understand that the only sound estimation is the energy consumption of Bitcoin is per block. Since a block can contain 0 to 10,380 Tx yet it consumes the same amount of energy per block (*see* [33a]). Therefore the minium Bitcoin transaction in PoW is currently $P_{min} \approx 115 kWh/Tx$ and the monthly average is $P_{avg} \approx 653 kWh/Tx$. See [34]

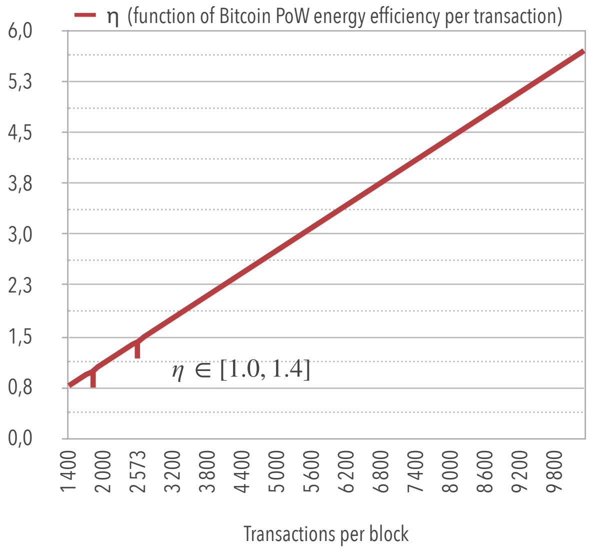
First conclusion, **Bitcoin is not used to its full potential. Since we can increase the transaction volumes ×4 without increasing its energy consumption.** Block size is underused today and Bitcoin adoption can grow without increase in energy. When this maximum limit is reached this will be the highest volume capacity Bitcoin can handle, and that's why we cannot extrapolate energy growth to be converted to more throughput above this cap. Bitcoin solved this limit by introducing Lightning Network at a layer 2 that we will cover in the next paragraphs.

Based on [0], we've defined that: the same *work* done by both systems is moving *money* through a displacement in *time*, instead of moving a physical object through space. The proper methodology in order to compare apples to apples is to compare the energy consumption relative to the settlement time of the 2 systems. Let's call ***Compared Energy Efficiency*** or *energy conversion efficiency* (η) a number without a unit obtained as a ratio of the useful *work* output of an energy conversion system compared to another system, here Bitcoin compared to the global monetary and payment system.

$$\eta = \frac{P_c t_c^2}{P_B t_B^2} = \frac{\Delta W_c \,.\, dt_c}{\Delta W_B \,.\, dt_B} = \eta_e \times \eta_d = \frac{A_c}{A_B}$$

Where, $\eta_e = \dfrac{\Delta W_c}{\Delta W_B}$ and $\eta_d = \dfrac{dt_c}{dt_B}$.

Note that *dt* is the displacement in *time* as in [0], *e* is for energy, *c* for classic system and B for Bitcoin. η_e, is the energy efficiency per transaction and η_d, is the duration efficiency per transaction (distance in *time*).



[D8] PoW *η energy efficiency vs Classical system, starting from the current lowest count of Tx/block up to the maximum block capacity (with current miner models mix)*

Note also that $A = P \,.\, t^2$ is called action in physics. The action is the momentum of the transaction times the displacement it moves through time and has dimensions of energy × time, and its unit can be in joule-second (like the Planck constant h).

Energy Efficiency is: $\eta = \eta_e \times \eta_d = \dfrac{A_c}{A_B}$ [35]

At a single transaction level, Bitcoin today is $\eta \approx 1.2 \times$ *more energy efficient than the Classical System with a range of* $\eta_B \in [1.0, 1.4]$ **[36]**

$\eta_{max} = 5.7$ *today* [36a]

"Eta" η can be analysed as energy efficiency or action efficiency as per [35]. That is temporal efficiency multiplied by work efficiency or the ratio of *action* A per transaction of both systems.

At its current capacity, Bitcoin PoW can use 412 times more energy per transaction than the electronic system and can finish the same work 413 times faster with a median block confirmation time of 418.44 seconds today (~7 minutes/block). At a block rate of 10 minutes, Bitcoin PoW is at least 288 times faster.

We can conclude that PoW layer 1 of Bitcoin is today $\eta_{Bitcoin} \approx 1.2$ times more energy efficient than the electronic system at the transaction level. Yet this efficiency is not yet used to its full potential today. If bitcoin adoption doubles then $\eta = 2$ becoming twice more energy efficient than classical system at a single transaction level. Today at current block size and if the blocks are filled to their maximum capacity $\eta_{max} = 5.7\times$ better energy efficiency than the classical system. In the future, old miner models will get eventually replaced by newer more efficient models and without increasing the hash rate nor the transaction count per block, $\eta_{Bitcoin} \approx 6.71$ times more energy efficient per transaction based only on PoW. Then 52.8 TWh/yr would consumed by PoW instead of 88.95 TWh/yr today, *see* [23a].

	Energy	Capacity	Tx Energy	Time	Efficiency
	TWh/yr	Tx/yr	kWh/Tx	Min	η
Classic	4981	3.146 Trillion	1.58	2880	**1×**
Bitcoin Current	89	133 Million	653	~7	**1.2×**
Bitcoin PoW	89	544.88 Million	115	~7	**5.7×**

[T2] *Bitcoin Energy Efficiency compared to the classical System. (Bitcoin current average and Bitcoin current maximum capacity PoW)*

Bitcoin Lightning vs Instant Payments

Let's take into account now Bitcoin Lightning network compared to Instant Payment (IP) schemes that are drastically increasing the finality time of the transaction respectively of both systems. The Lightning Network has an important capability to scale up exponentially the transactions throughput above Bitcoin layer 1, yet it does so without growing in a proportional rate to the energy input.

It's important to understand first how Lightning transactions work. Lightning leverages existing Bitcoin transaction channels between peer to peer payers and payees to group additional Bitcoin Lightning transactions in a single Bitcoin PoW transaction on the main Blockchain. For example, if Alice A wants to pay Georges G, 1000 satoshi (=0.00000001 bitcoin ≈ 4$ today) Lightning will find the fastest open channel that's already executing transactions on its path to include the amount and make the payment instantly on this channel. From A to G the transaction can be direct between 2 nodes if they have an open prepaid channel between them, if not and the transaction needs to go to the other end of the globe, it's assumed that ≤6 hops are required from A to reach G:

$$A \xrightarrow[1]{hop} B \xrightarrow[2]{hop} C \xrightarrow[3]{hop} D \xrightarrow[4]{hop} E \xrightarrow[5]{hop} F \xrightarrow[6]{hop} G$$

Today Lightning is in production and live but is still in its early adoption with 36,852 nodes (14,950 nodes with public IPs) and 83,601 open channels. Lightning network capacity is today 141 millions $ with an average channel capacity of 8,183$ (0.213 BTC). An instant payment transaction on Bitcoin costs only 1 satoshi as a median base fee and takes a fraction of a second to finalise.

A Bitcoin Lightning node can be modelled using a raspberry pi with an SSD usually used by the nodes. Such a unit consumes about 5W if both CPUs are busy which is not the case all the time. A transaction is processed in less than a second roughly in ≈500 *milliseconds* per transactions as the duration of actual processing. Given the estimation of 6 hops:

$E_{L2}(Lightning) \approx 6 \times 5W \times 0.5s = 0.00416667Wh$ per transaction[43] or 7.5W of power, if the transactions are treated in a single mode. This is about 480,000 times less energy than a classical payments transaction.

E_{L2}(**Lightning**) ≈ 0.000004167 **kWh/Tx** **[35]**

Let's compare this result to an instant payment transaction for instance in the eurozone (SEPA SCTInst scheme). A payment transaction is initiated at an online banking account relying on several banking servers doing compliance, online banking backend, core banking layer 1 and 2, instant payments servers such as Payment as a Service PaaS and the server for instant payments that calls the

[43] This is a minimal energy cost today without counting for smartcontracts added value services above Bitcoin Lightning that will become possible thanks to new protocols under development such as TATO and Watchtowers.

CSM to reach the central bank instant payment system to check 1st the reachability of the payee's bank, thus making several calls among at least 5 to 10 hops just for the reachability checks. Then ounce the reachability is OK between payer and payees banks, the instant payment order is given and the processing goes through the same hops in addition to more depth reaching the core bank main layer (we do not account for the notifications of the payer and the payee of the execution of the transaction since these are sensibly the same also for Lightning). The total number of hops can be about more than 20 hops between heavy duty servers in data centres and mainframes in addition to centralised systems at the central bank linking everyone. For eurozone instant payments SCTInst scheme, the clearing and settlement mechanism CSM can be through an intermediary like STET in France, linking banks to the TIPS system at the European Central Bank. Note also that an instant payment transaction is not always a final transaction, it guarantees the finality in advance since it uses mirror accounts at CSM of the banks accounts at central banks. The complete finality is usually delayed especially when the central bank system is not available.

Note that comparing Bitcoin Lightning to Faster Payments or Instant Payment Schemes without counting the underlying channel closer on Bitcoin using PoW is a valid approach. The rational is that a Bitcoin Lightning transaction is final at layer 2 and its an option to write it later on the layer 1 of Bitcoin with PoW or to close the channel. Also saying that an instant payment in classical system can take 7 seconds instead of 48 hours is sometimes wrong because in reality it can takes in certain cases 3 hours to 24 hours to settle completely with central bank money while on Bitcoin Lightning it is final after a fraction of a second and on the worst case it can take 10 minutes (optionally) with a channel closing on the main Blockchain.

Based on the preceding analysis of Lightning and Instant Payments we can consider that instant payments energy consumption is equivalent to the same old classical system energy consumption since it uses the same hardware and banking infrastructure but only prioritises and accelerates certain transactions part of the workflow. In addition the means of payment by itself as instant payment is still not yet widely adopted in payments globally since it is still missing additional complementary services such as Request to Pay, link to card payment initiation and PoS acceptance solutions. Finally an instant payment is today a local payment and is not available for cross border transactions. On the other hand Bitcoin Lighting is still also in its beginning of development with certain issues like stuck transactions that cancels after a longer time than 1 second. As we see both innovations are competing but still not 100% stable and not deployed to a large scale.

Comparing payments throughput, we saw in [10c] that the classical system has a capacity of 3.146 Trillion Tx/yr that might seem to correspond to 99,759 Tx/s. But for a large part these transactions are bulk payments and not individual peak capacity. Note from [4d] that the maximum capacity today of card payments authorisation is limited to ≈48,891 Tx/s. At the same energy input in both systems, compared to Bitcoin, the Lightning Network can handle 1,000,000 Tx/s in a single channel that is 20.45 times more capacity than the classical system and still 345,600 times faster or at least 14 times faster than Instant Payments[44].

Lightning is 14 × faster than Instant Payment	**[37]**

And total Energy consumption of Bitcoin and Bitcoin Lightning is sensibly the same:

$$E_{L1L2}(Bitcoin) = E_{L1} + E_{L2} = E_{L1} + \epsilon_{L2} \approx 88.95TWh/yr$$

Theoretically if we consider that Instant Payment is fully adopted worldwide even for cross border payments, the maximum scale up capacity is estimated by Swift to be 1000 Tx/s. That is a maximum throughput of 31.53 Billion Tx/year. This shows a scalability ceiling for current electronic centralised payment systems limiting the adoption of instant payments for about only 1% of current global payment transactions. In order to increase this limit important hardware and architecture changes are required from core banking, online banking, payment hubs, Swift GPI to central bank systems.

In order to evaluate the precise total average energy efficiency of an Instant Payment transaction, we can omit all cash, CIT and ATMs related energy and keep only banking, PSP, and Interbanking energy

[44] Which is technically sometimes not final in 7 seconds and require clearing.

consumption. This leads to 3,860 TWh/yr for a maximum capacity of 31.53 Billion Tx/year. Note that this lowered total energy consumption means that there are no more banknote and coins, which is not realistic since all central banks are promising the opposite. Since IP cannot replace all electronic payment transactions we are forced to maintain the cash servicing energy. We will consider the additional energy required to service IP negligible.

$Energy_{min}(IP) \approx 3860$ TWh/yr	[38a]
$Energy_{avg}(IP) \approx 4981$ TWh/yr	**[38]**
$Energy_{tx}(IP) \approx 158$ kWh/Tx	**[39]**
Capacity(IP) ≈ 31.53 Billion Tx/yr	[40]

Note that [38] is only theoretical since today cross border transactions are not instant payment ready and the total number of instant payment Tx is below maximum capacity of [40]. Average energy of a single IP transaction [39] is between 120 and 158 kWh/Tx based on [38a] and [38] respectively and the theoretical today's maximum in [40].

By applying the same method to a Lightning transaction, we will not consider the single layer 2 energy and its 0.000004167 kWh/Tx. For Bitcoin we will also take both layers leading to:

$Energy_{L1L2}(Lightning) \approx 88.95$ TWh/yr	**[41]**
$Energy_{tx}(Lightning) \approx 0{,}00282059$ kWh/Tx	**[42]**
Capacity(IP) ≈ 31.54 Trillion Tx/yr	[43]

Conclusion

Today when we transfer 1 dollar from a payer to a payee, there is no real[45] transfer of value done between the two. This is due to the fragmented nature of electronic monetary system today. What should take place during the transaction in the electronic system is a change of ownership of the asset called money, but in reality it is a conversion of commercial bank money supervised by the central bank. The payment executes a *burn* of this private electronic money conserved by the bank of the payer and then a different operation of *earn* is performed for the equivalent amount with a different privately issued electronic money by bank of the payee. The settlement of this *burn* and *earn* is achieved through a distinct transaction[46] executed between the bank of the payer and the bank of the payee using their own accounts at the central bank.

The payee, although he received the payment, will never have a direct claim on it. It's an amount that he's is lending to his bank, equivalent to a *promise:* "*I owe you*" (IOU). His bank owes to him this amount of money at the central bank. This is an important difference between Bitcoin and the classical money system. A Bitcoin transaction between a payer and a payee is a direct transfer of the cryptoasset: *bitcoin* functioning as cryptocurrency without the need of any trusted third party. The nature of the cryptocurrency Bitcoin is cryptographically different. It is a token or real value and not money as debt or a promise, on the contrary it is final with a direct ownership of the intrinsic value of the asset a feature that the electronic money system does not offer consistently except in banknotes and coins. That's why comparing Bitcoin to electronic money and payment system is not comparing 100% similar systems. Yet in this paper we've endeavoured to compare their common promise only from an energy efficiency point of view, ignoring all additional features of both. For instance Bitcoin is also a programmable form of money with less complexity of its value chain and participants, allowing the commoditisation of the whole classical payment system and allowing additional services such as smart contract and programmability. In contrast, Instant Payments is not, and require additional services such as Request to Pay scheme and also a link to a card schem e which are not built into the classical system yet.

Globally, results prove that **Bitcoin uses 56× less energy than the classical system** even with Lightning and Instant Payments inclusion to the introduction. And without comparing to any other cryptopayments consensus mechanism using proof of stake.

[45] Money in cash form (banknotes and coins) are indeed directly exchanged between Alice and Georges but they are not 100% direct exchange of money. They are a direct exchange of central promise of the face value on the paper or coin guaranteed by the central bank. So there's no intrinsic value being instantly exchanged.

[46] This transaction groups all the Alice to Georges transaction but bundled with all transaction between these 2 banks after the netting of their values

	Total Energy	Total Capacity	Tx Energy	Tx Duration	Comparing Tx Energy	Comparing Speed	Energy Efficiency
	TWh/yr	Tx/yr	kWh/Tx	Seconds	η_E	η_S	η_{EE}
Classical System †	4 981	3.14 trillion	1.58	172 800	1 ×	1 ×	**1** ×
Bitcoin PoW Current	88.95	133 Million	460 to 653	418.44	290.6 × to 412.5 ×	413 ×	**1.2** ×
Bitcoin PoW Best Possible	52.8	545 Million	97	600	61.2 ×	288 ×	**4.71** ×
Instant Payment ‡	4 981	31.53 Billion	158	~7	99.8×	24 686 ×	**247** ×
Bitcoin L1+L2 Lightning	88.95	31.54 Trillion	0,00282	~0.5	0.0010576 ×	345 600 ×	**† 194 Million** × ‡ 1 Million ×

[T3] *Figures of Instant Payment & Lightning: both systems used to their maximum capacity to demonstrate full potentiel and scalability. Hypothetically every Tx is switched to its fastest mode in each system*

Today at a single transaction, level Bitcoin Proof of Work is in average 1.2× more energy efficient than a classic electronic payment transaction and can go up to 5× with more adoption or natural replacement of older mining units with more efficient hardware already available.

When Bitcoin Lightning and Instant Payments are included in the benchmark, and by simulating that they are used to their highest capacity in both systems we find that a Bitcoin Lightning transaction is in average 345,000 times faster than classical system and 14 times faster than an instant payment transaction. In addition **Bitcoin Lightning scales far higher than Instant Payments** with a theoretic capacity of 31 Trillion Tx per year for Lightning compared to 31 Billion Tx per year for Instant Payments. This capacity limitation is mostly due to the Swift like cross border systems limitation in throughput at ~1000 transactions per second. In our estimation we've used 1000 Tx/s as a global maximum for instant payments, but in reality different regional or country systems may be unable to reach that capacity for instance, European Central Bank instant payment scheme (TIPS) is estimated to process up to a maximum average of 500 transactions per second. As a consequence, if both systems are used to their maximum capacity, the energy cost of a single instant payment transaction becomes much higher than a classical payment and requires ~158 kWh/Tx. Bitcoin scales better and manages to decrease drastically down to 0.00282 kWh/Tx on his 2 layers combined (so including PoW).

In conclusion, Lightning at a single transaction level allows Bitcoin to become **194 Million × more energy efficient than a classical payment and up to 1 million × more energy efficient than an instant payment Tx.**

We can observe that the classical system is over optimised to consume less energy per transaction to operate trillions of transaction per year in relative slow speed between 2 to 7 days to complete. This over optimisation and specialisation causes it to be fragmented, fragile and less capable of scaling up today to instant payments. While Bitcoin has a higher power output ratio and is capable to scale very efficiently using Lightning Network, thanks to the PoW layer of its main Blockchain.

References

"2020 Annual Review and Consolidated Financial Statements" — SWIFT Annual Review

"A Map of Forex Traders: Where Are the 9.6 Million Online Traders?" — brokernotes.co, 2022

"Armored Vehicles Are Key to the Cash-in-Transit Industry" — *The Armoured Group*, 2022

"Assessing IBM's POWER8, Part 2: Server Applications on OpenPOWER" — *Johan De Gelas*, Sept 2016

"Average number of individuals employed per bank in Europe (EU28) in 2018, by country" — Statista

"Banknotes and coins circulation" — *ECB*, 2022

"Benchmarking Commercial Building Energy Use Per Square Foot" — *IotaComm*, August 20, 2020

"Bitcoin, totem & tabou — Que présage l'essor des cryptomonnaies ?" *Institut Sapiens*, Fev 2018

"Bitnodes estimates the relative size of the Bitcoin peer-to-peer network by finding all of its reachable nodes."

"Cambridge Bitcoin Electricity Consumption Index" — *Cambridge (CBECI)*, 2022

"Circulation velocity and how you can influence it" — *De La Rue*, 2018

"Climat: des emails à l'e-book, l'impact du numérique n'a rien de virtuel" — *Science & Avenir*, Mars 2016

"Community Banks Get Creative With Unused Branch Space", Independentbanker.Org, January 2, 2018

"Comparing Bitcoin & Lightning energy usage to the real world" — *Co-Authored by Oliver Barratt & Danny Scott*, 2021

"Confirmed Transactions Per Day" — blockchain.info

"CZ Binance" — twitter.com, March 14, 2022

"Diebold Innovation Leads to World's Greenest, Most Power-Efficient ATM" — prnewswire.com, March 2014

"Electric trucks like the Tesla Semi are 'pointless both economically and ecologically,' according to a vehicle-tech expert" — *Johannes Kaufmann and Qayyah Moynihan, Business Insider Deutschland* , Apr 3, 2019

"En moyenne, en France, un trader gagne 1 million d'euros par an" — *lepoint.fr*, 2014

"Energy hogs: Servers vs. desktops vs. set-top boxes" — *Patrick Thibodeau*, JUL 6, 2011

"Energy Losses Due to Imperfect Payment Infrastructure and Payment Instruments" — *Oleksandr Melnychenko*, Oct 9, 2021

"Everything you need to know about cross-border payments" — *emerchantpay*, 2021

"Fourteen Facts about the US Penny" — *Design Life-Cycle*, 2014

"From Home to Work, the Average Commute is 26.4 Minutes" — *US Bureau of Transportation*, OCT 2003

"Gestion des stocks et loi normale" — *JY Baudot*

"Global POS Terminals and Wireless M2M Market Report 2021: POS Terminal App Stores are a Potential Game-Changer" — *Research and Markets*, December 2021

"Glossaire Des Cryptopaiements" — *France Payments Forum*, 2020

"Guidelines for the next generation of Real-Time Retail Payments Systems (RT-RPS)" — *Swift*, 2015

"How long do wire transfers take?" — Swift

"How Many Dollar Bills Are in Circulation?" — *TitleMax*, 2017

"How Many Watts Does An Air Conditioner Use?" — *Bardi*, 2021

"How much is the total power supply consumption of an ATM machine?" — Quora, 2019

"How Much Money Is In The World Right Now?" — *Go Banking Rates*, Feb 2022.

"How much power does a computer use? And how much CO2 does that represent?" — energuide.be

"Identifying IT Markets and Market Size by Number of Servers" — *Applied Computer Research, Inc.*, 2011

"Le grand paradoxe – ou pourquoi le règne du cash est loin de s'achever" — *Terra Nova*, 2021

"Leading banks in the United States as of December 31, 2021, by number of employees" — Statista

"Lightning Network Explorer" — *explorer.acinq.co*, 2022

"Loomis Our business" — web.archive.org, 2014

"Loomis vs Brinks Comparison" — *macroaxis.com*, 2022

"Miners profitability" — asicminervalue.com

"Money Minting - The process of producing coins", *CFI*, 2022

"Number of credit, debit and prepaid cards in circulation worldwide from 2017 to 2021, with forecasts for 2023, 2025, and 2026" — Statista

"Number of individuals employed by credit institutions in Europe (EU28) from 2009 to 2019" — Statista

"Real-Time Lightning Network Statistics" — *1ML.com*,

"Répartition du nombre de salariés du groupe bancaire BNP Paribas dans le monde de 2017 à 2020" — Statista

"Scaling Renewable Energy" — equinix.com, 2022

"Share of cash transactions at POS (points of sale) in the euro area in 2016 and 2019" — Statista

"Société Générale Fact Sheet", *Société Générale*, 2022

"Spatial proximity and distance travelled: Commuting versus non-commuting trips in Flanders" — *Kobe Boussauw, Frank Witlox*

"STET Fact Sheet" — *STET*, 2021

"Study on the payment attitudes of consumers in the euro area (SPACE)" — ECB, Dec 2020

"TARGET Instant Payment Settlement User Requirements" — *ECB*, 2017

"The carbon footprint of bitcoin" — De Nederlandsche Bank, *Juan Pablo Trespalacios and Justin Dijk*, 2021

"The Energy Consumption of Blockchain Technology: Beyond Myth" — *Johannes Sedlmeir, Hans Ulrich Buhl, Gilbert Fridgen, Robert Keller*, 2020

"The Hidden Expense of Energy — Print Is Costly, Online Isn't Free" — *The Scholarly Kitchen*, 2022

"The lifespan of money", *Giesecke+Devrient GmbH*, 2022

"The State Of Lightning" — *Arcane Research*, Oct 2021

"Total Hash Rate (TH/s)" — blockchain.info

"United States Data Center Energy Usage Report" — Shehabi et al, 2016; Shehabi et al, 2018

"Visa Data Centers: The engine rooms of Visa's global commerce network", *Visa*, 2017

"Visa Fact Sheet" — *Visa*, 2022

"Visa Green Bond Report" — July 2021

"What is Energy and How Much do You Use?" — *Sustainability Exchange*, 2022

"What Is The Bitcoin Block Size Limit?" — *Bitcoin Magazine*, Aug 17, 2020

"What is the diesel consumption per kilometer of trucks?" — *Bridgestone Webfleet Solutions*, Feb 2020

"Which consumes more power: Banks or Bitcoins?" — *Zodhya*, April 2018

About the Author

(*) Michel KHAZZAKA (@kneisseh), founder of Valuechain a Cryptopayments consulting enterprise and YouTube channel. Computer engineer specialised for 17 years+ in payments security and innovation. Lead of Cryptopayments workgroups at several french payments and inter-banking entities. An international speaker and trainer, has given lectures and courses in 5 continents on blockchain and cryptocurrencies, some of which at Sorbonne and Paris Dauphine universities in Paris and the American University of Beirut.