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The impact of blockchain in the energy sector

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Abstract

The blockchain technology was born in 2008 to validate Bitcoin transactions, the first and most popular cryptocurrency. Its development was initially correlated to the original purpose to serve as alternative transaction validation method, but its nature of an algorithm with high cybersecurity potential has made it increasingly interesting in many other fields of applications.

The blockchain can have a key role in the progressive digitalization of goods and services, and its versatility is greatly appreciated by programmers and companies. Many applications are now consolidated or in advanced phase of study such as smart contracts, digital ledgers and tokens transactions. They can be used in many fields of applications: cybersecurity, election and voting, healthcare, supply chain, marketing, real estate, mobile and gaming. In the energy sector blockchain can significantly improve operations in fields as wholesale and decentralized energy trading, with a particular attention in microgrids management, energy management in general, metering and billing, green certificate, carbon trading and the management of the Internet of things and Internet of vehicles.

On the other hand, the blockchain technology is characterized by a high energy cost caused by its protocol of validation, called Proof-of-Work. This aspect can be a great obstacle to blockchain diffusion, because the development of new energy-intensive technologies contrasts with sustainability and emissions reduction to mitigate the climate change.

The aim of this work is to analyse how blockchain works and in particular how much energy its diverse applications consume, what countries are investing in this technology and to study how blockchain impact in the energy system of those countries that have chosen to use it.

The energy consumption for the Proof-of-Work validation protocol is calculated using Bitcoin as case study, being this cryptocurrency the principal blockchain user. Bitcoin difficulty, hardware efficiency and Bitcoin hashrate are the parameters used for the analysis. Bitcoin difficulty characterizes the computational effort to validate a new block, hardware efficiency is the efficiency related to the velocity of the block validation and Bitcoin hashrate is the number of block validations per second. Two future scenarios are described: a first one that follows the trend that both difficulty and hashrate have shown starting from 2021 and a second one in which the two parameters have lower values because they follow the trend line of all the historical data starting from 2017.

All consumption forecasts are also divided between the main countries in which Bitcoin mining pools are located (United States, China and Kazakhstan, followed by Canada, Russia, Germany, Malaysia and Ireland).

Proof-of-Work consumptions are then compared with Proof-of-Stake consumptions, a different protocol of validation that is significantly less energy intensive, to understand if it can be a proper alternative to reduce electric consumption.

1 Introduction

Blockchain technology is born in 2008 to validate Bitcoin transactions, the first and most popular cryptocurrency [1]. Its development has been initially correlated with its original purpose, but being an algorithm with high cybersecurity potential, in the last years it has become more and more interesting for many other fields of applications.

Blockchain can have a key role in the progressive digitalization of goods and services, its versatility is greatly appreciated by programmers and companies have started to invest in this technology. Many applications are now consolidated or in advanced phase of study.

On the other hand, blockchain is characterized by a high energy cost caused by its protocol of validation, called Proof-of-Work. This aspect can be a great obstacle to blockchain diffusion, because the development of new energy intensive technologies contrasts with sustainability and emissions reduction to mitigate the climate change.

The aim of this work is to analyse how blockchain works, what are its principal and future fields of application, what countries are investing in this technology and first to study how blockchain impact in the energy system of the countries that have chosen to use it.

A special attention is dedicated to the high electric consumption of the Proof-of-Work protocol, with estimates of the actual values and future projections, worldwide and for any country involved, in order to understand if blockchain development is sustainable and compatible with the characteristics of global and local energy systems and with political and ethical goals.

1.1 What is a blockchain?

A blockchain is basically a chain of blocks, each of which contains some information.

According to NISTIR 8202 [2]:

Blockchains are tamper-evident and tamper-resistant digital ledgers implemented in a distributed fashion (i.e., without a central repository) and usually without a central authority (i.e., a bank, company, or government). At their basic level, they enable a community of users to record transactions in a shared ledger within that community, such that under normal operation of the blockchain network no transaction can be changed once published [2].

Each block contains an index, the previous block's hash, a timestamp, a nonce value, and its own hash (hashing is a one-way function in that it encodes text without a way to retrieve the original value) [3]. Each block is connected to the previous block through the previous block's hash, so all blocks are connected like a daisy chain. The first block in the chain, called the genesis, does not have a previous block, so the previous block's hash is NULL. The index is a unique number for each block. The index of the first block is 0, the second block is 1, the third block is 2, and so on. The timestamp is the date and time when the block is created, and the nonce is a 32-bit (4-byte) integer whose value controls the outcome of the calculated hash of the block. Each block uses its index, the previous block's hash, its data, its timestamp, and its nonce value to feed into a hash function, to create its own hash. A hash cannot be reversed. If someone gets the hash of the current block, there is no way they can figure out the information in the block that was hashed.

Hashing technique plays a vital role in creating what is called immutable data storage. A hash value is computed and locally stored inside each block using its content and the hash value of its immediate predecessor. The hash function is designed in such a way that it is very complex to compute, but easy to verify. This sequence of hash functions for the chronologically ordered blocks thus forms a publicly available, easy to verify mechanism for protecting the contents of the blockchains. Due to the chronological dependency on the previous block, the hash value stored at each node cannot be tampered in isolation. The publicly verifiable sequence of hash functions associated with the blockchain makes any illegal modification easily identifiable. Also, any such tampering would demand the re-computation of the entire hash chain, which is computationally very expensive.

The blockchain system is composed by four main components [4]:

- A node application
- A shared ledger
- A consensus algorithm
- A virtual machine

Each computer inter-connected through the Internet becomes a node and needs to install and run a computer application specific to the chosen blockchain system.

The distributed ledger is a data structure managed inside the node application. There is one specific ledger for any blockchain system that rules the way interactions are done.

The consensus algorithm is implemented as a portion of the node application, by providing the "rules of the game". Different systems have different methods for attaining consensus. Participation in the consensus-building process, the method for determining the world state of the system, can be vested in a number of different schemes: proof-of-work, proof-of-stake, proof-of-elapsed-time.

A virtual machine is a representation of a machine (real or imaginary) created by a computer program and operated with instructions embodied in a language. It is an abstraction of a machine, held inside a machine.

Blockchains are also classified following permission criteria [5]:

- Public blockchains
- Permissioned blockchains
- Private blockchains

Public blockchains are open for anyone to participate at any level and have open-source code that their community maintains.

Permissioned blockchains are different because their core code may or may not be open source.

Private blockchains have instead their membership closely controlled.

1.2 Centralized and Decentralized Systems

Blockchain is known to be a decentralized system, but first of all the difference between centralized and decentralized systems should be established.

Three points of view should be considered [6]:

- Technical
- Political
- Logical

The technical point of view basically considers how many nodes (computers) are connected to the system, how many are strictly necessary to avoid system failure and so on.

The political point of view looks if there it is a single node, or a small group, that has the authority to rule all the other nodes, in this case the system is centralized, or on the other hand if all nodes have the same authority, that is the case of a decentralized system.

From a logical point of view instead it is important to understand if a system works even if it looses some parts. A logically centralized system cannot loose some important nodes without damages, while a decentralized can works even if some parts are cut.

The blockchain system is technically and politically decentralized, but is logically centralized because the common agreement, that becomes the rules that every node must respect, makes all the nodes to work as a single computer.

Decentralized systems are more resistant because they don't have point of failure, but they are more difficult to be controlled.

1.3 Mining

Miners are intermediaries necessary on blockchain-based networks. The transmission of digital currencies, the storage of data, and the execution of smart contracts are facilitated by miners, and in doing that they receive block rewards and fees based on their work [7].

The authority to adopt new software that amends or modifies a blockchain’s underlying protocol is retained by miners due to the decentralized nature of blockchain network. They can rewrite the transaction history of the shared database or implement additional controls that regulate the way to store, to process and to record informations. If a proof-of-work consensus mechanism rules the blockchain network, the majority of miners can agree to change the rules of the protocol or ignore any transactions related to a specific account.

To increase the probability of receiving a block reward miners organize themselves into large, centralized mining pools that aggregate the computational resources of multiple machines. These mining pools could cooperate or work against each other to fork a blockchain. In this way a problem of control appears governments have to regulate the way of working of mining pools to balance and to control the decentralized blockchain network. Instruments such as penalties and rewards can be effective, but the global and decentralized nature of the blockchain is a big task.

The most important algorithm that rules the building of a blockchain must satisfy various aspects [7], this protocol is known as Proof-of-Work, and it follows different steps [8]:

- Validation
- Reward
- Punishment
- Competition
- Peer control

Through validation only valid blocks can be added to the chain, this is achieved by validation rules:

- Validation rules for transaction data
- Validation rules for block headers

Data that describe a transaction are established by specific rules because they must satisfy formal and semantic correctness and authorization.

The formal and semantic correctness of the block headers is supervised by other specific rules that establish the way information is added to the blockchain. The verification of the proof of work and the hash puzzle are fundamental.

To solve the hash puzzle, unique for any new block, a big computational effort is required, so peers must spend energy, time and money in this task. A reward for their effort is a good way to incentivize their work, that is necessary for building the chain. A specific algorithm rules the reward system.

On the other hand, it is necessary to punish nodes that damage the building of the chain. The punishment can simply be the loss of previous reward or the absence of reward.

A competition is needed and the node that win will receive the reward. The competition is divided in two steps and both must be won:

- Speed competition
- Quality competition

The first node that is able to solve the hash puzzle, unique for any new block, is the winner of the speed competition and the only participant of the quality competition.

When the speed competition is over all the nodes that have lost become the referees of the quality competition. They have to validate or not the new block: if the new block respects validation rules, that is added to the chain and the reward is assigned to the winner of the speed competition, otherwise the speed competition starts again.

Due to the decentralized nature of the blockchain system there is not central control authority, so every node that composes the network has the authority to supervise the other nodes, this method is known as peer control.

Being a decentralized system there is not a central clock that establishes the nodes working rhythm, but the messages that arrive at any nodes when a hash puzzle is resolved carry out this function. In this way all nodes work at the same speed, the quality competition starts for all at the same time.

1.3.1 Alternative algorithm protocols

Proof-of-Stake is a protocol in which the computational work is replaced by a random selection process, in which the mining success is related to how much nodes have invested in the system. This approach has been developed to reduce energy consumption, as we will see later [8] [9].

Proof-of-Authority works with a special permission required to make changes to the blockchain that replaces the computational work. Permissions are granted via voting to the chosen members. This approach betrays the decentralized original nature of blockchain being far more centralized [8].

In Proof-of-Elapsed Time protocol validator nodes request a waiting time from a trusted function. The node with the shortest wait time adds the new block. The environment controls if claiming leadership is legitimate and so a problem of centralization exists [8].

Proof-of-Activity is a hybrid approach that mixes Proof of Work and Proof of Stake. If a block template is empty of transactions generated by miners that follow Proof of Work, then the block is validated by Proof of Stake [8].

Proof-of-Burn uses nodes as validators paying in coins that are “burned” and cannot be reclaimed [8].

Proof-of-Capacity obliges validator nodes to commit hard drive spaces to increase their chances to produce blocks [8].

2 Blockchain utilization

As previously said blockchain technology was developed for the cryptocurrency market, but many other fields of application are possible.

The most explored application areas until now are [10]:

- Coins
- Tokens
- Ledgers
- Smart contracts

2.1 Coins

Bitcoin was the first cryptocurrency and the reason for blockchain creation. At the moment there are more than 2000 cryptocurrencies with a market cap of billions of dollars [10].

It is likely that in the near future money transfers will become mainly digital, blockchain technology is the natural solution for this [11][12].

2.1.1 Cryptocurrency Regulation

In many countries cryptocurrencies are not legal tender, they are considered as securities (fungible, negotiable financial instruments that hold some type of monetary value) and their exchange is legal. This is the case of United States, United Kingdom, Canada, Singapore, South Korea and India. Other countries such as Australia, Japan, El Salvador and Switzerland considered cryptocurrencies as legal tender and have specific regulations about that. China instead considers all cryptocurrency and their exchange illegal despite being one of the countries with the highest mining activity. In the European Union the regulation varies from member-state [13].

El Salvador uses geothermal energy to generate the electricity required by the very energy-intensive mining activity, the quote of renewable energy is declared as 95% [14].

2.2 Tokens

Tokens are accounting units; they represent the right to perform some operations. They are especially useful in authentication and access processes (security tokens). They can be created with unique data to be a personal key that is not interchangeable (nonfungible tokens); blockchain can be used in this way because it is an immutable chain of custody and proof of ownership. Tokens can be used also to represent the digital or physical values of various assets and the balance between them: stocks, options, digital obligations, flat currencies, ownership rights, rights for a service [10].

2.3 Ledgers

Ledgers are books or collections of accounts in which account transactions are recorded. Digital ledger, as traditional cloud storages, are commonly centralized, so the user must trust the entity that controls the ledger. Using the blockchain technology decentralized ledgers can be created. The efficiency of this approach has been proved by networks such as Pirate Bay, that exchange and store digital assets illegally, obviously this can be done in a legal and legitimate way [10].

2.4 Smart contracts

Digital contracts signed using blockchain technology have the advantage of the absence of the third figure that must validate them (notary, banker, attorney, loan officer) [10].

Starting from these areas many future fields of application can be explored and exploited [8], [10], [15], [16], [17]:

- Cybersecurity
- Supply chain improvement
- Election and voting
- Healthcare
- Marketing
- Real estate
- Mobile
- Gaming
- Energy system

2.5 Cybersecurity

The blockchain technology gives a private cryptographic key to each user instead of using a password for authentication processes. In this way the security against hacker attacks is greatly increased. The verification of data is also improved and expedited; this can be used to enhance bureaucracy matters.

2.6 Supply chain improvement

A private blockchain decentralized ledger can be very useful for supply companies: they can divide the supply chain and work in different areas (chain of custody for ownership assets, product identity and monitoring).

2.7 Election and voting

Elections can be done digitally with blockchain. In this way the verification of who is voting, the transparency and the security of the outcome calculation are greatly implemented.

2.8 Healthcare

In this area private blockchains can be very useful to fight against the drug counterfeiting phenomenon and in drug storing.

2.9 Marketing

The fact that decentralized blockchain is an immutable data store can be used for data analysis in the market area.

2.10 Real estate

The same considerations that are made for voting are valid for the real estate industry.

2.11 Mobile

Privacy can be increased using blockchains, an eventual censorship of the mobile app’s store can be avoided with the decentralized system.

2.12 Gaming

Advantages of the immutable data store are well accepted by gaming industries, PlayStation Network and Microsoft have begun to use blockchain technology.

2.13 Energy systems

Various applications are possible in the energy sector [8], [18]:

- Wholesale energy trading and supply
- Decentralized energy trading
- Energy cryptocurrency
- Metering and billing
- Green certificates and carbon trading
- Energy control and management
- Internet of things and internet of vehicles

2.13.1 Wholesale energy trading and supply

Wholesale energy markets require a great number of third-party intermediates such as trading agents, brokers, price reporters, exchanges, banks, regulators and logistic providers; this is due to the very complex nature of the procedures that regulate the system.

In transactions manual post-processing is a part of the procedure, so blockchain technology in the shape of distributed ledgers and smart contracts can be a very innovative and useful solution to ameliorate and accelerate all procedures. More safety for agreements, automatic payments, reduce time of delivery and transparency of transactions can be some improvement of blockchain use [8].

But some problems are present: first, the number of transactions supported by blockchain is an order of magnitude smaller than that of traditional electronic payments, this is due mainly to the proof-of-work consensus; proof-of-stake can be a valid alternative to fix this problem. Second, wholesale trading is overly complex so, at the beginning at least, blockchain can be more efficient in smaller and local contests, as explained in the next chapter [8].

2.13.2 Decentralized energy trading

The development of the new renewable energy technologies, in particular solar, wind and biomass, in a distributed way needs a proper system that can manage all the energy exchanges and control them efficiently [19]. A prosumer (a consumer with a power generation device such as photovoltaic or wind turbine) can perform a power trading with a consumer directly if there is physical power connection (Figure 2) [18]. For an intermediary utility provider becomes difficult to control this type of energy connections. Blockchain however is designed to perform peer-to-peer transactions without a central control, this can be particularly useful for a local community. Participants of the transactions can be divided into three types: power unit, generating unit and matching unit [19]. The power unit is the energy demander (a small power company or an average household), the generating unit is the energy supplier (a small wind plant or photovoltaic generator) and the matching unit is the transaction medium, in this case managed by the blockchain, that controls the energy exchange ledger. After transactions rules have been declared via smart contracts, automatic transactions are possible [20]. With blockchain use prosumers can have access to the energy market, that was a privileged field for big energy companies due to prohibitive costs [21]. End-users are also incentivised in taking part in the local energy market [8], [22]. They can also know and monitory the origin of the energy purchase, from what sources it is generated. Some limitations are present in the form of scalability and speed of transactions supported by blockchain system [8].

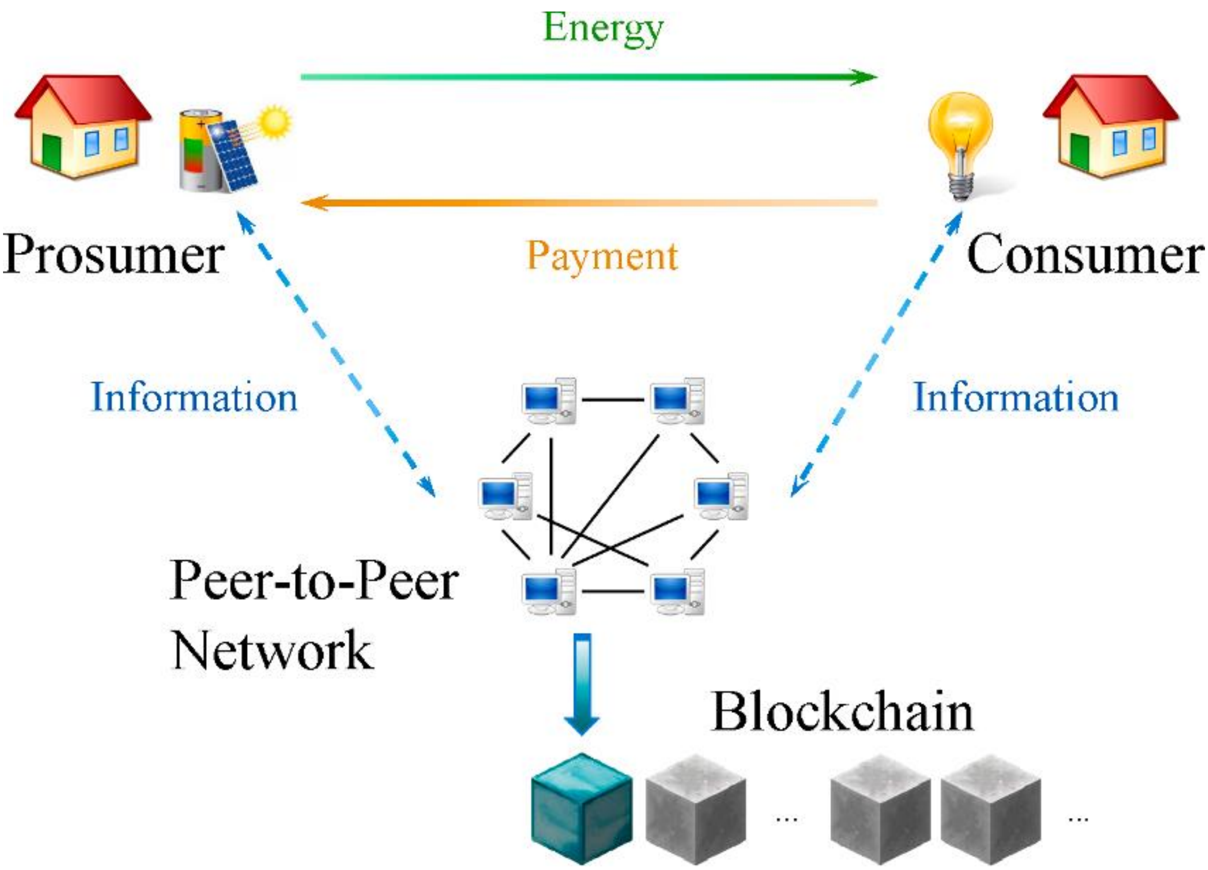


Figure 1: Peer-to-peer energy trading between a prosumer and a consumer [18].

2.13.2.1 Decentralized energy trading in microgrids

A microgrid is defined as group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and can work in eighter grid-connected or island mode [23]. Unlike the local community setting, physical connections are not necessary in microgrids [18]. Virtual microgrids can guarantee localised energy production and consumption, decreasing distribution and transmission losses. They can also supply energy services to users in case of grid problems [8]. Using blockchain the local energy market is similar to stock market: the interest of buyers and sellers is recorded in an order book; consumers can change their price preferences in real time; locally produced energy is allocated to the highest bidder; the lowest allocated bid is the market clearing price for each 15 minutes intervals [8], [22]. Microgrids controlled by blockchain are in development in various country: United States, UK, Australia, New Zealand, Japan, Germany, France, Denmark, Netherlands, Switzerland, China and Thailand.

2.13.3 Energy cryptocurrency

Cryptocurrency can also be used in energy trading and energy application [8], [18]. They can be assigned to those who have the highest stake in a system or who provide the most socially useful service, for example producers that generate renewable energy can be rewarded with specific cryptocurrencies [8]. This is an incisive method to tokenised assets that aims to create new markets.

The UK startup 4NEW has created KWATT, a cryptocurrency that represents 1 kW of electricity per year of waste to power energy plant co-located with a cryptocurrency mining farm. It can be used to sell the energy to UK national grid or to mine other cryptocurrencies [8], [24].

The Gibraltar startup WePower has developed a platform that tokenise and then trade renewable energy. Electricity can be purchased with tokens or they can be exchanged for fiat currencies or other cryptocurrencies [8], [25].

MPAQ and NRG are two tokens created by ImpactPPA; the first one is sold to investors that raise capital for communities that have not access to electricity, the second one is used by users to buy electricity and track renewable energy production data [8], [26].

A cryptocurrency based on the economic activity of manufacturing energy storage ultracapacitors has been developed by Farad; it has the purpose of encourage the exploration of new energy storage solutions [8], [27].

One SolarCoin is granted for each MWh of solar energy produced. This cryptocurrency has been launched by SolarChange in 2014 [8].

RecycleToCoin, created by the Blockchain Development Company, is instead a cryptocurrency linked to the recycle of plastic, steel and aluminium. A QR code is used to grant the reward after recycled items are delivered to the collection points [8]. Actually (2023) it is inactive [28].

GREEN is a token proposed by Greeneum for granting green certificates and carbon credits [8].

2.13.4 Metering and billing

Smart meters can use blockchain technology to improve storing, buying and selling electrical energy. A specific ledger manages transactions and data exchange guarantying transparency and users' privacy [18]. Manual metering and billing are more expensive and insecure because exposed to many potential errors compared to the blockchain decentralized ledger [29], [30]. Various company has started to use smart metres linked to blockchain for electricity, water and heat distribution, for example: Bankymoon, SunChain, Pylon Network, M-PAYG, Engie, CGI and Eneco [31], [32], [33], [34], [35]. However, blockchain smart meters can be a challenge because a total new infrastructure must be built and permission problems may arise due to the decentralized nature of the blockchain system; for this reason, cybersecurity companies are working in this area [8], [36].

Many companies around the world accept cryptocurrencies for energy payments: BAS Nederland, Enercity, Elegant, Marubeni. In some cases, there are bill reduction from 4% to 6% [8], [37], [38], [39], [40].

2.13.5 Green certificates and carbon trading

A green certificate is a commodity product that authenticates the amount of renewable electricity generated by producers. They follow the EU guideline 2009/28/EC and they are stored in national registries [41]. They can be traded between producers or between producers and customers. Blockchain can be used in this trade with advantages equal to that seen for metering and billing [18].

Carbon trading is a way to control carbon emissions. A price is imposed for carbon emissions to reduce them [42]. Blockchain can manage this system too and can be very useful for small energy producers that have difficulties in claiming carbon credits due to excessive costs associated with the procedure [8], [18].

Nasdaq was the first global stock exchange to develop green certificate trading [43]. Other companies are active in green certificate and carbon trading: Veridium, Poseidon, DAO IPCI, CarbonX and Grid Singularity [44], [45], [46], [47], [48]. The Chinese Energy Blockchain Lab has partnered with IBM to create a platform that can reduce Chinese national carbon market by 30% [8], [49].

2.13.6 Energy control and management

Voltage control, frequency regulation, reactive power optimization and active power sharing are parameters that can be controlled by a decentralized system with more efficiency that a centralized one [18].

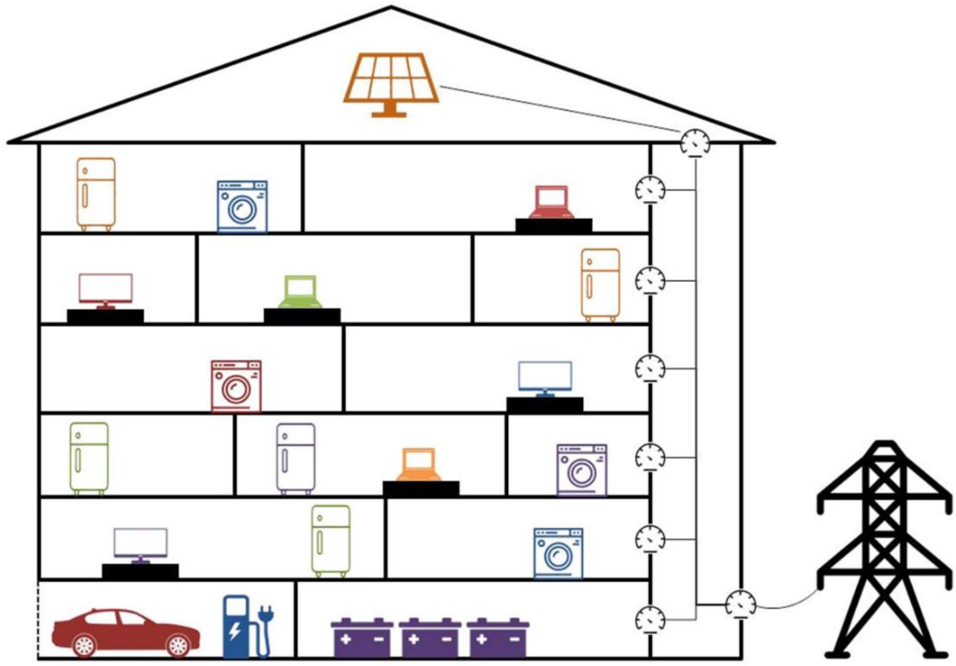
Promising results has been showed for a grid connected with blockchain architecture and the use of smart contracts. The energy demand is adjusted in near real time by enacting the expected energy flexibility levels and confirming all the demand response agreements. A pure peer-to-peer decentralized energy trading system without intermediates has become possible [50]. Users can check in real time power consumption and the system is secure against attacks [51]. The system guarantees the same performances of a welfare-maximizing centralized dispatched avoiding the risk of monopoly price manipulation [52].

Companies active in the development of blockchain software for energy management include: PONTON, Grid Singularity, TenneT, Sonnen, Vandenbron, PROSUME, EvolvePower, Power Ledger and Electron [8], [53], [54], [55].

2.13.7 Internet of things and internet of vehicles

Internet of things promotes the development of smart homes, smart cities, smart manufactures and smart grids and smart vehicles (Internet of vehicles). With many devices connected to the Internet problems of privacy, reliability and data integrity may arise; classical centralized systems become inefficient with remarkably high data volumes. A decentralized database like blockchain instead, very suited for peer-to-peer transactions and so also for machine-to-machine communications, can be especially useful also in this area with the same advantages seen for the yet cited fields of application [8], [18], [56], [57].

Blockchain technology that manages an Iot platform is represented in a study by Mattila, consisting in a local autonomous marketplace of a housing society with rooftop PVs, electric vehicles, flexible appliances, a battery energy system and smart meters. Blockchain is able to distinguish energy generated by each device and to manage the trading between them. For this application a private blockchain is suggested [58].



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Many companies are active in linking blockchain with IoT: Filament, Stock.it, Siemens, Innogy RWE, Samsung, Dajie, Power Ledger, Fortum, AdptEVE, Green Running, Tavrida Electric, Qiwi, Wanxiang, Oli, Wirepas and Daisee [59], [60], [61], [62], [63], [64], [65], [66], [67], [68].

Electric mobility is especially adapted for blockchain use. Share&Charge is a platform, created by Innogy Motionwerk, that allows peer-to-peer transactions between electric vehicles users and private charging stations. Smart contracts run the charging station network meanwhile drivers are allowed to use the system by an electric wallet. Automatic billing is achieved and any member of the system can control instantaneously all transactions [8]. Other companies active in electric mobility with similar solutions are: Alliander, Car eWallet, PROSUME, Energo Labs, Everty and Power Ledger [69], [70], [71], [72].

3 Present and future perspectives

Blockchain has now reached technology maturity and as earlier said it has many fields of use.

A 2018 report from Deloitte [73] shows how the blockchain technology is seen from senior executives of various companies. Companies are divided in normal enterprises and ”emerging disruptors”, these are companies that typically have started as a start-up and then have growth quickly, because well-funded and managed and well connected to key stakeholders. They have become big players in the market. They have the ability to take advantage of new and innovative technology, blockchain being an example.

Figure 3 shows the planned investment for 2019 in blockchain technology [73].

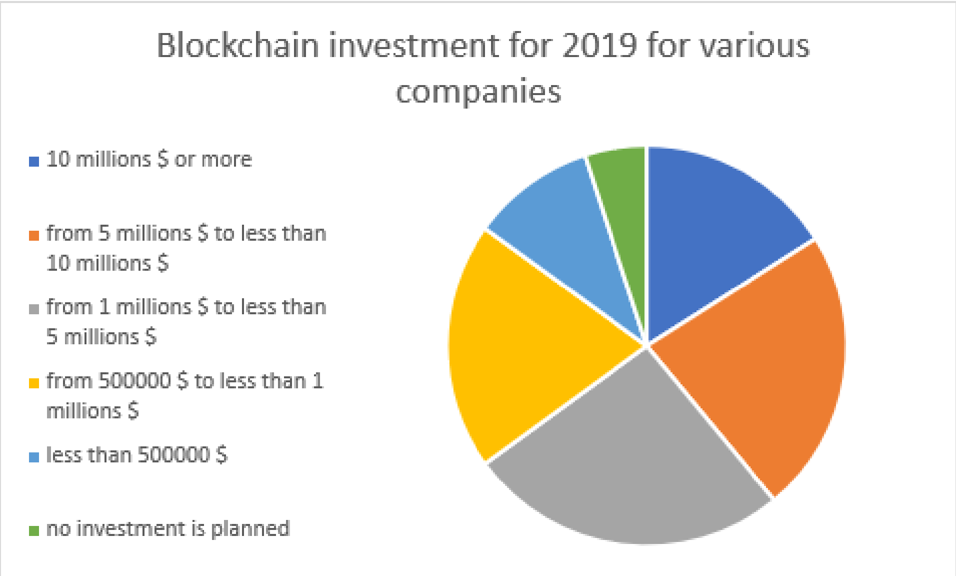


Figure 3: Blockchain investment for 2019 for various companies

Most of the senior executives of the emerging disruptors companies told that blockchain will have a great role in future.

Countries that are the vanguard in the blockchain sector are China, Canada and Mexico [73].

The subsequent report of Deloitte regarding blockchain (2021) [74] talks about the rapid increase of influence of the blockchain technology in the financial services industry. Companies and especially banks must adapt themselves to exploit the innovative technology that is disrupting and it is invading overwhelmingly the financial sector.

As previously said, China is giving substantial attention to blockchain technology. A special collective learning session has been held recently by the CPC Central Committee to discuss the trend of blockchain development [75]. The focus was considered the in-depth integration of blockchain technology into the real economy. As 2020 finance services were ranked first among sectors using blockchain technology, with a percentage of 36% [75]. This confirms what said in the 2021 Deloitte report. The number of Chinese companies engaged in blockchain activities rose from 17 in 2016 to 214 in 2020.

A recent study concerning the so called “Global South” has shown the number of blockchain companies in those countries [76] (data shown in Table 1).

Table 1: Number of blockchain companies in the "Global South"

Economic region	**Number of blockchain start-ups**
East Asia	231
East Europe and Central Asia	36
Latin America and the Caribbean	135
Middle East and North Africa	55
Southeast Asia	229
Sub Saharan Africa	70

East Asia and Southeast Asia are the principal centres of blockchain development, with more than 500 companies, followed by Latin America. The great number of start-ups has been created between 2017 and 2018 [76]. The principal fields of application in the Global South are financial applications, data management and sustainable energy [76].

4 Blockchain energy consumption

Blockchain technologies are generally strongly energy intensive. Being based on software devices, energy consumption is represented by electricity. Mining activities require a huge amount of energy. The proof-of-work system is very safe at the cost of high energy intensity, so other systems were created to bypass this problem, especially the proof-of-stake protocol.

To analyse the energy consumptions of a blockchain is therefore important to divide between proof-of-work protocol and other protocols.

Other sources of consumption are present, such as data storage consumption. In all distributed systems data storage redundancy is needed to enhance robustness against failures. A copy of all system data is required for all blockchain node meaning an enormous storage cost [18].

4.1 Proof-of-Work protocol energy consumption

A way to estimate Bitcoin energy consumption is to set a lower and an upper bound that represent minimum and maximum of the supposed consumption [77]. Since it is very difficult to determine how much energy is consumed without knowing exactly the number of nodes that compose the network, the properties of their computers and the effective effort that they put in mining activity.

The lower bound-energy consumption can be calculated as in Equation 1:

$$Total\ power\ consumption\ =\ Total\ hash\ rate\ \times\ Min\ energy\ per\ hash\ (1)$$ [i]

Where the hash rate is the expected value of the minimum frequency of calculation to solve the cryptographic puzzle and the min energy is the minimum energy required for that. These data are easily observable online [78].

The upper bound is instead calculated as in Equation 2.

$$Total\ power\ consumption\ \leq\ \frac{Block\ reward \times Coin\ price + Transaction\ fees}{Avg.\ blocktime \times Min.\ electricity\ price}\ (2)$$

considering miners to be honest and rational [77]. The block reward is the number of cryptocurrency coins one receives for solving a puzzle, the coin price and the transaction fees are data publicly observable, the average blocktime is the medium time for solving a puzzle.

With this approach the lower bound annual electricity consumption is 60 TWh obtained from Coinmarketcap data for 2020 [77]. The estimate of the upper bound is instead approximately of 125 TWh per year, for Bitcoin only [79]. Differently from the lower bound, the upper one is overly sensitive to economic circumstances being dependent on the coin price and on the cost of transaction fees. This correlation has clearly been noticed in the drop of financial market at the start of the Covid pandemic, when Bitcoin prices rose by 40%.

These estimates are performed considering only the energy necessary to the mining activity, without considering the energy required to maintain operative all nodes of network. Mining pools (great agglomerates of mining hardware machines) do not usually make public details and data about their work, but some reports talk about an electric consumption of 800 MWh per day to keep the nodes operativity. This energy is negligible compared to the mining energy that is orders of magnitude higher [80].

According to other estimates Bitcoin annual energy consumption for 2019 was 61,74 TWh [81]. This value is similar to that computed with the lower bound found through Equation 1. Ethereum consumption is instead almost ten times lower even though they both use the same consensus; the difference is due to different hashing algorithms and different trading volumes [82], [83]. Ethereum trading volume is approximately a third of that of Bitcoin in 2023 [79]. A single Bitcoin transaction is said to consume the same energy as 100 thousand VISA transactions [81].

More recently data from 2021 compare annual electricity consumption of Bitcoin and Ethereum with that of selected countries [84], [85]. They can be seen in Table 2.

Table 2: Comparison between electric energy consumption of selected countries and Bitcoin and Ethereum energy consumption.

Country or cryptocurrency	**Electric energy consumed [TWh]**
China	7500.00
USA	3989.60
India	1547.00
Italy	300.00
Taiwan	237.55
Vietnam	216.99
South Africa	210.30
Thailand	185.85
Poland	153.00
Egypt	150.57
Malaysia	147.21
Bitcoin	135.12
Sweden	131.79
Switzerland	56.35
Ethereum	55.01
Ireland	33.00

The comparison is also done with VISA transactions [84] (Table 3).

Table 3: Comparison between energy consumption of Bitcoin, Ethereum and VISA transactions

Transaction method	**Transactions/day**	**Electric energy consumption [TWh]**
Bitcoin	0.4×10^6	135.12
Ethereum	1.23×10^6	55.01
VISA	500×10^6	197.57

It can be noted that the daily number of transactions of Bitcoin and Ethereum are respectively 0.08% and 0.25% of that of VISA. A single Bitcoin transaction is estimated to consume electricity as much as 1195657 VISA transactions, a single Ethereum transaction is instead equal to 83574 VISA transactions [84].

A study by Alex de Vries estimates that in 2021 2.9 million specialized hardware devices work on mining consuming approximately 114 TWh of electricity [86].

One other model has been developed to calculate the future mining power [83], with a specific formula for Bitcoin (Equation 3).

$$P_{Bitcoin} = n_{min} \times P_{HW} = \frac{D_{Bitcoin} \times 2^{32}}{\Delta t \times R_{HW}} \times P_{HW} = \frac{D_{BTC} \times 2^{32}}{\Delta t \times \eta_{HW}} \; (3)$$

$P_{Bitcoin}$ represents the power demand, n_{min} the number of miners, P_{HW} the power demand of a certain mining hardware, $D_{Bitcoin}$ the difficulty of the Bitcoin network, Δt the mining time of a block, R_{HW} the hashrate and finally η_{HW} the mining efficiency. The block difficulty is an indicator for the computational power needed to generate a new block [83].

There is a similar equation for Ethereum (Equation 4).

$$P_{Ethereum} = n_{min} \times P_{HW} = \frac{D_{Ethereum}}{\Delta t \times R_{HW}} \times P_{HW} = \frac{D_{Ethereum}}{\Delta t \times \eta_{HW}} \; (4)$$

Three scenarios are considered for Bitcoin: a first in which the rise of mining difficulty is exponential, a second in which is linear and finally a stagnation one [83].

Even for Ethereum six scenarios based on hardware efficiency and block difficulty are considered [83].

A Chinese study estimates that in 2024 Bitcoin energy consumption in China will be around 300 TWh [87]. These estimates are calculated through a specific model developed in Vensim software [88] that use network hash rate, block size, transaction fee and transaction difficulty as parameters; these data are obtained from btc.com site [87], [89]. Additional parameters regarding Chinese economy are obtained from the World Bank [87]. Results of the study show how will be impossible to China to fulfil Paris Agreement objectives in a business-as-usual scenario [87].

The nature of the proof-of-work protocol, that requires a complicated cryptographic puzzle to be solved, does not ensure that in future energy consumption will decrease, because the puzzle to be solved must always be difficult and so the process is energy-intensive by nature. In 2020 proof-of-work protocol was 75% of the cryptocurrency sector [81].

An estimate of Bitcoin consumption is available at [90]:

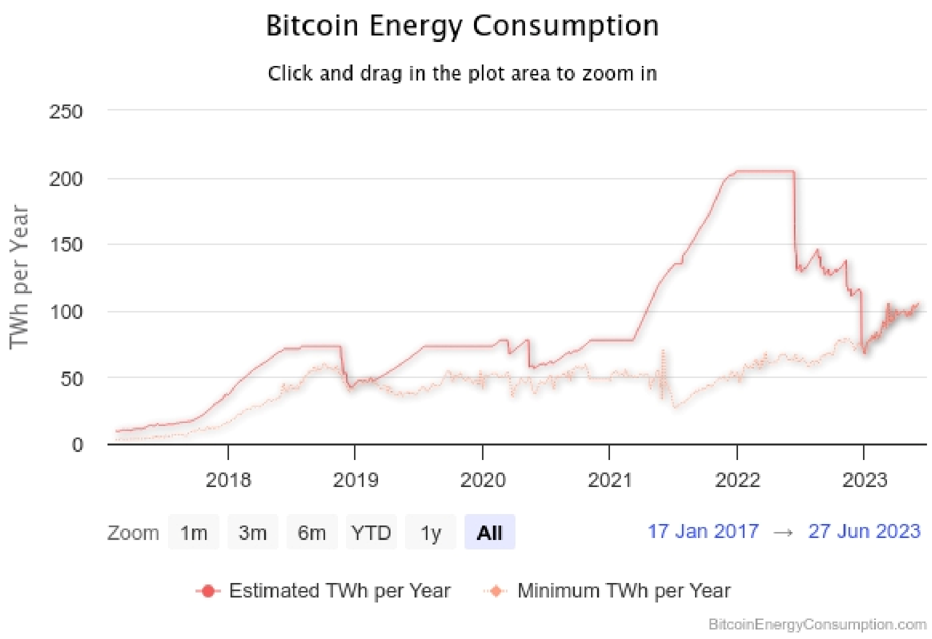


Figure 4: Bitcoin energy consumption [90]

As can be seen in Figure 4 there are two consumption curves: a first referred to the minimum consumption and a second to the estimated consumption. The minimum is calculated from the total network hashrate, assuming the only machine used in the network is Bitmain's Antminer S9. On February 13, 2019, the minimum benchmark was changed to Bitmain's Antminer S15, followed by Bitmain's Antminer S17e per November 7, 2019 and Bitmain's Antminer S19 Pro per October 31, 2020 [90]. The estimated is calculated on the premise that miner income and costs are related. Since electricity costs are a major component of the ongoing costs, it follows that the total electricity consumption of the Bitcoin network must be related to miner income as well [90].

Starting from mid-2018 the estimated worldwide consumption was near 75 TWh per year and increased to near 200 TWh in 2022. In 2023 there has been a great fall to near 100 TWh [90]. This is attributable to the high volatility of Bitcoin price, that influences mining and so electric consumption. War in Ukraine, inflation in Western countries, Chinese Evergrande company bankrupt and legislation against mining activity are the most probably causes to this price crack [91], [92].

4.1.1 Proof-of-Work energy consumption localization for Bitcoin

China was the principal country in which mining pools were located, but after the 2021 ban of the Chinese government the situation changed [93], [94].

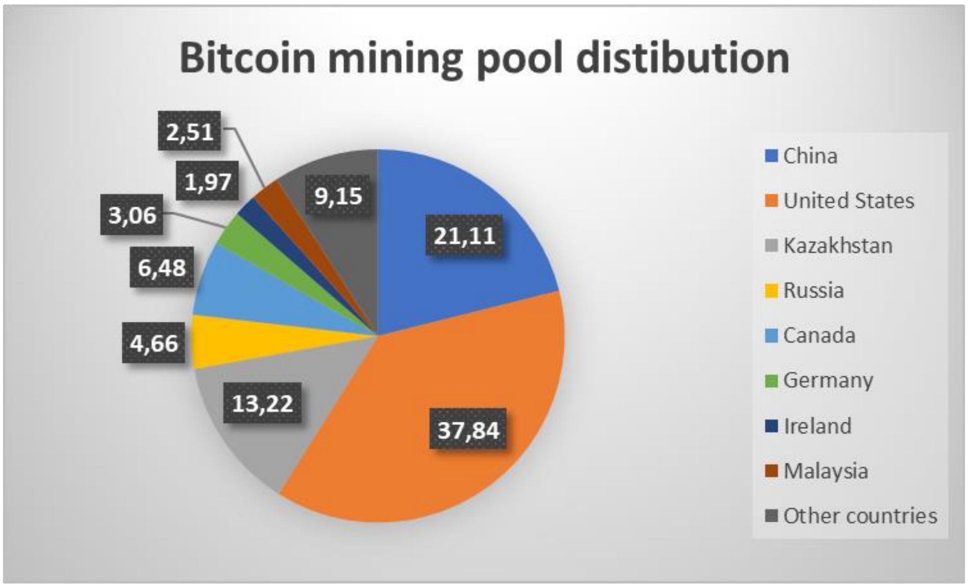


Figure 5: Distribution of Bitcoin mining pools in 2023 [95]

In 2020 78.89% of the mining pool of the entire world was in China, mostly due to the fact that specialized hardware manufacturers are located there and the cost of electricity is low than in Western countries. [87] Mining pools preferred to be located in the coal-area, near to the hardware manufacturers, instead of the less developed hydroelectric-area [87].

As can be seen in Figure 6, coal is still the main energy source in the country, with a share of more than 70% in the last ten years. Oil and natural gas together represent 13% of total energy consumption and all non-fossil fuel have slowly increase their share to 17% [96], [97], [98], [99].

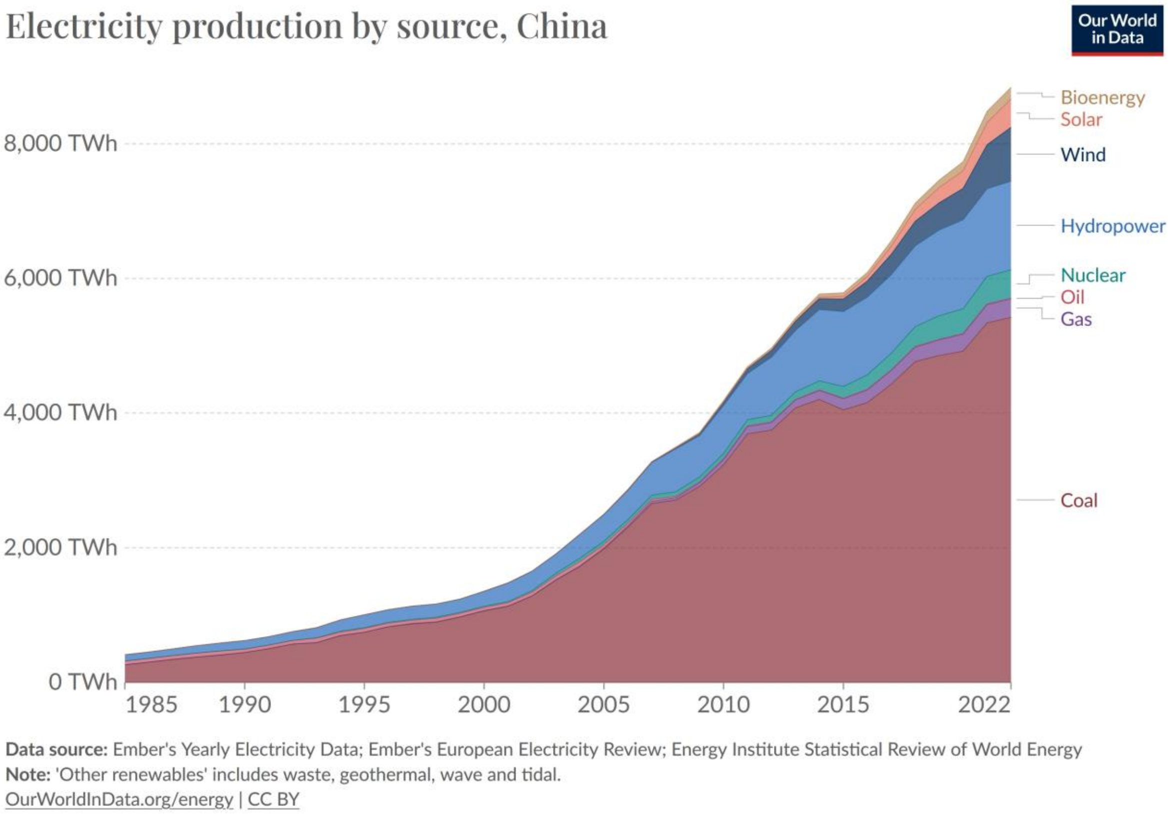


Figure 6: Electricity production by source in China

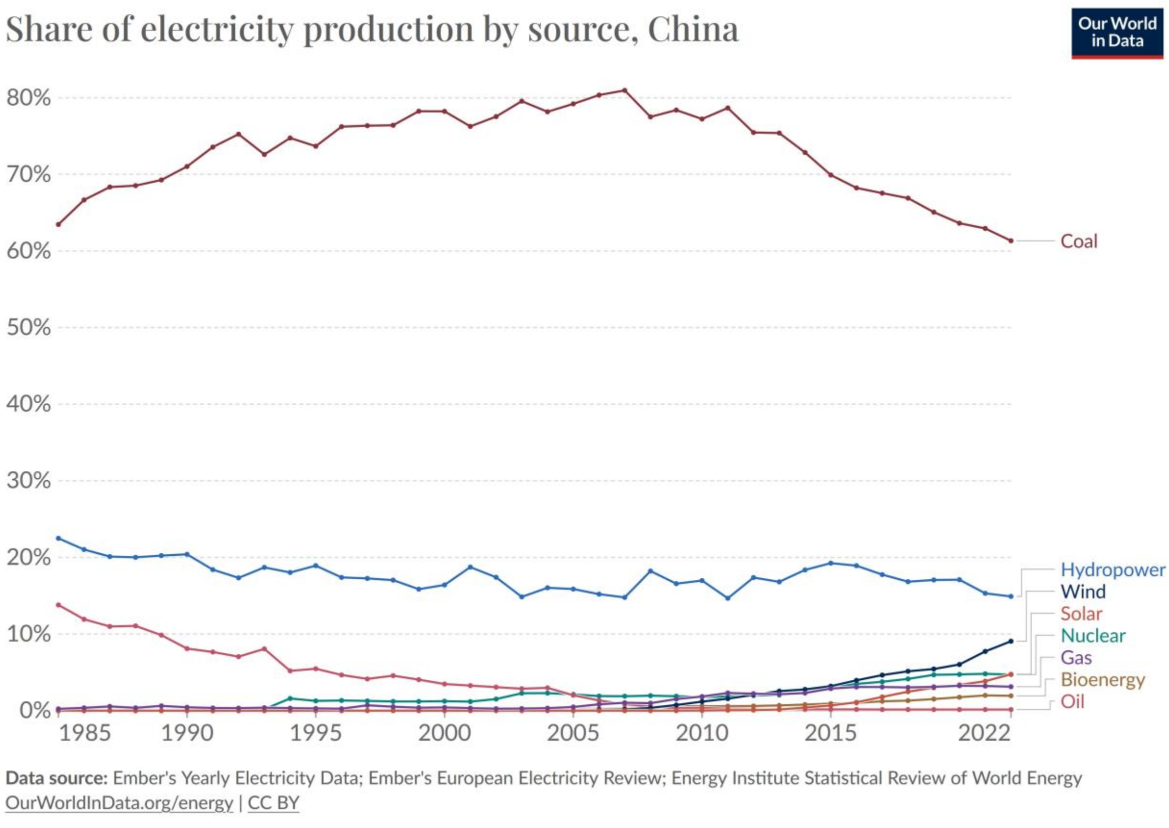


Figure 7: Share of electricity production by source in China

China joined the Paris Agreement in 2015, so it is obliged to decrease CO_2 emissions per unit of gross domestic product by 60-65% of 2005 emissions by 2030 and to reach carbon neutrality by 2060 [94], [96]. As previously said, citing the Chinese study developed through the Vensim software, the expected proof-of-work energy consumption will have made this impossible to happen [87].

For that reason, in May 2021 the Chinese Government banned crypto trading and mining forcing mining pools, that were principally in Inner Mongolia, Xinjiang and Sichuan provinces, to shut down permanently or to relocate in other countries [93], [100].

Despite the ban however, mining activity is still performed in China, this is due to the fact that using a virtual private network (VPN) mining pools are able to conceal their location routing their internet activity through a server in another country [101]. More recent data estimate that mining activity in China represents 21.11% of the total activity worldwide [95].

After the Chinese ban most of mining pools relocated into the United States. Actually 37.84% of the total mining power is installed there [95], [102]. New York is the epicentre of US mining activity but also Texas and Montana have welcomed mining pools [103], [104]. Chelan Country, in the Washington State, has seen a quick phenomenon of mining pools installation; new infrastructures have been rapidly built in a way to be called "energy consumption boomtowns". Miners have chosen Chelan Country thanks to the great and more economic power supply generated by hydroelectric dams of the region. The local community has raised many doubts regarding mining pools installation because the principal activity of the country is agriculture and citizens are worried about climate damages and electricity price rise [104].

Actually, gas is the principal energy source of United States (40%) followed by coal (20%) and nuclear (18%) as can be seen in Figure 8 [98].

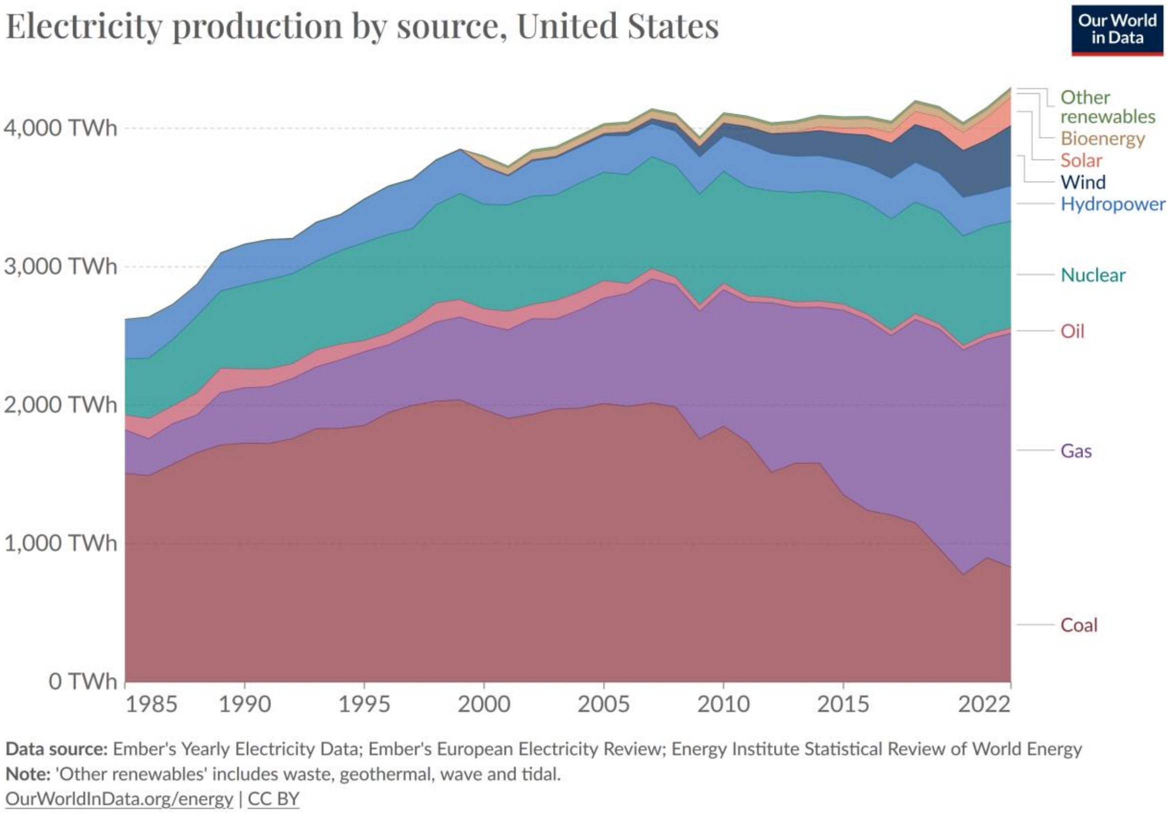


Figure 8: Electricity production by source in United States

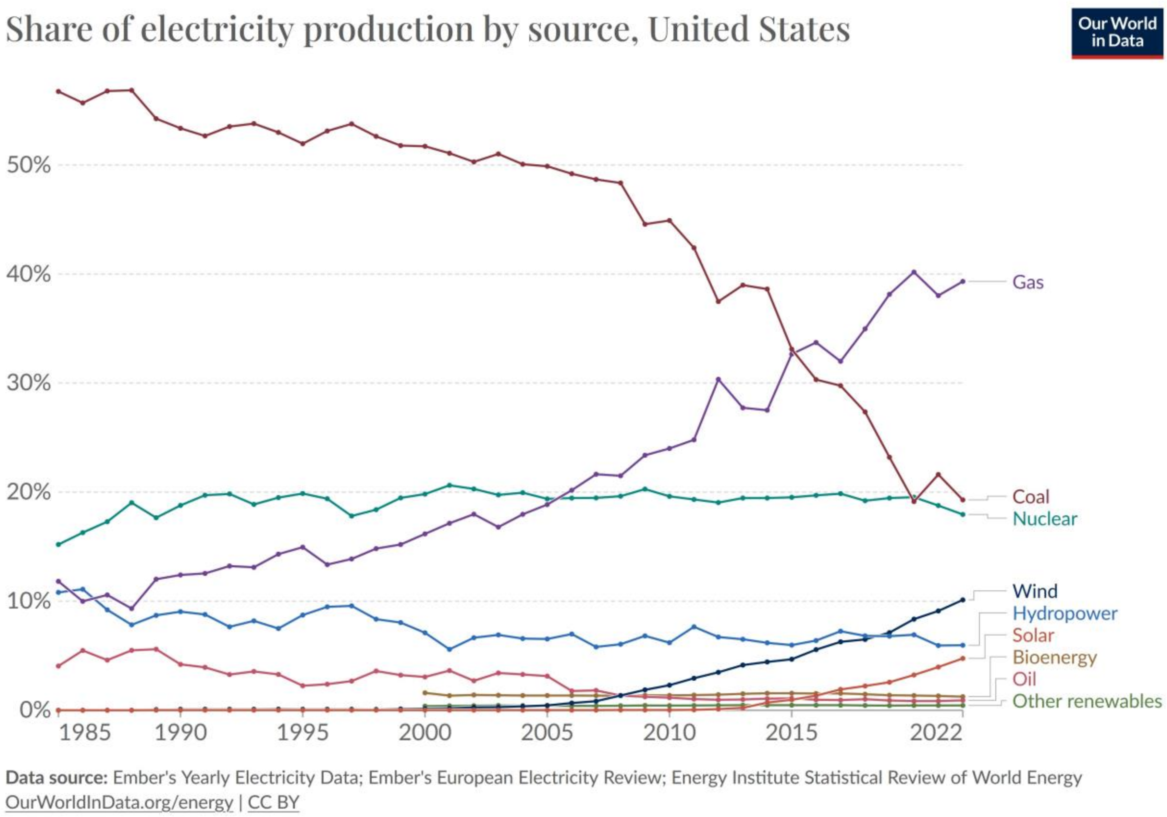


Figure 9: Share of electricity production by source in United States

A US governmental report estimates mining consumption to be about 0.9% to 1.7% of total electricity usage in September 2022 [102]. If mining activity will continue to increase using only electricity generated from fossil fuels United States risk to not achieve Paris Agreement objectives if the US energy system does not evolve. For this reason, American administration has been started to legislate to limit or eliminate the use of energy-intensive consensus protocol for cryptocurrency mining [102].

Kazakhstan also has seen increased its mining activity after the Chinese ban. Actually, it is the third country in the World for mining pools presence with a quote of 13,22% [95].

The region selected to instal mining pools is the north-east of the country, especially the city of Ekibastuz, where a lot of coal plants are present, as a legacy of the Soviet Union era, that left the country with a constant surplus of power supply at a very low cost [105].

Coal and gas are the two main sources used in Kazakhstan, with 60% and 30% of share respectively (data shown in Figure 10) [98]. Kazakhstan is the second country in the World for Uranium possession. Its reserves are of nearly 81500 tons (13% of worldwide reserves) [106], however the nuclear is mostly unused with a share smaller than 5% [98].

Just after the Chinese ban the Kazakhstan quote of worldwide hashrate was 20%. A single facility at full work absorbed from the grid 150 MW, five time the power needed for the city of Ekibastuz, the total consumption of mining pools became the 7% of the entire Kazakhstan demand. This caused numerous troubles as localized blackouts, due to grid inefficiency. This made the government to block and cut off a great number of mining pools from the grid [105].

However, after the full legal recognition of crypto assets in the country in September 2022, mining activity has been partially relaunched [105].

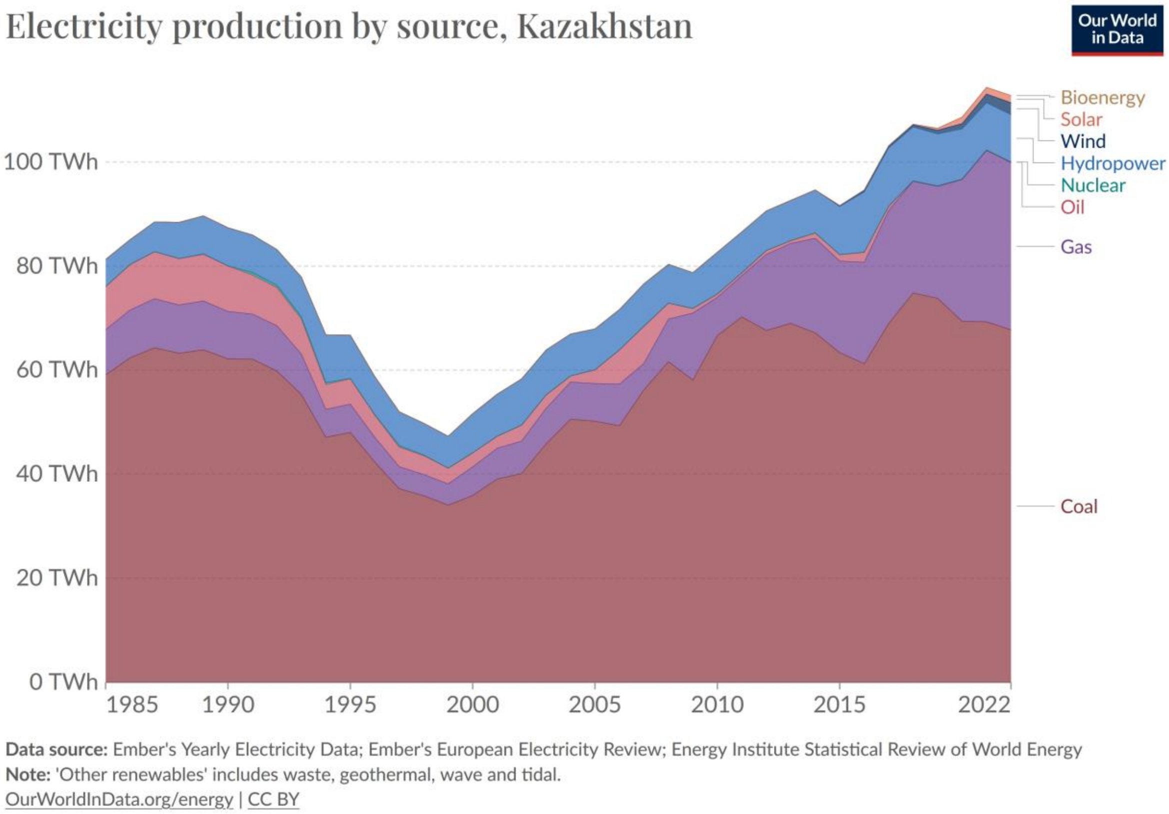


Figure 10: Electricity production by source in Kazakhstan

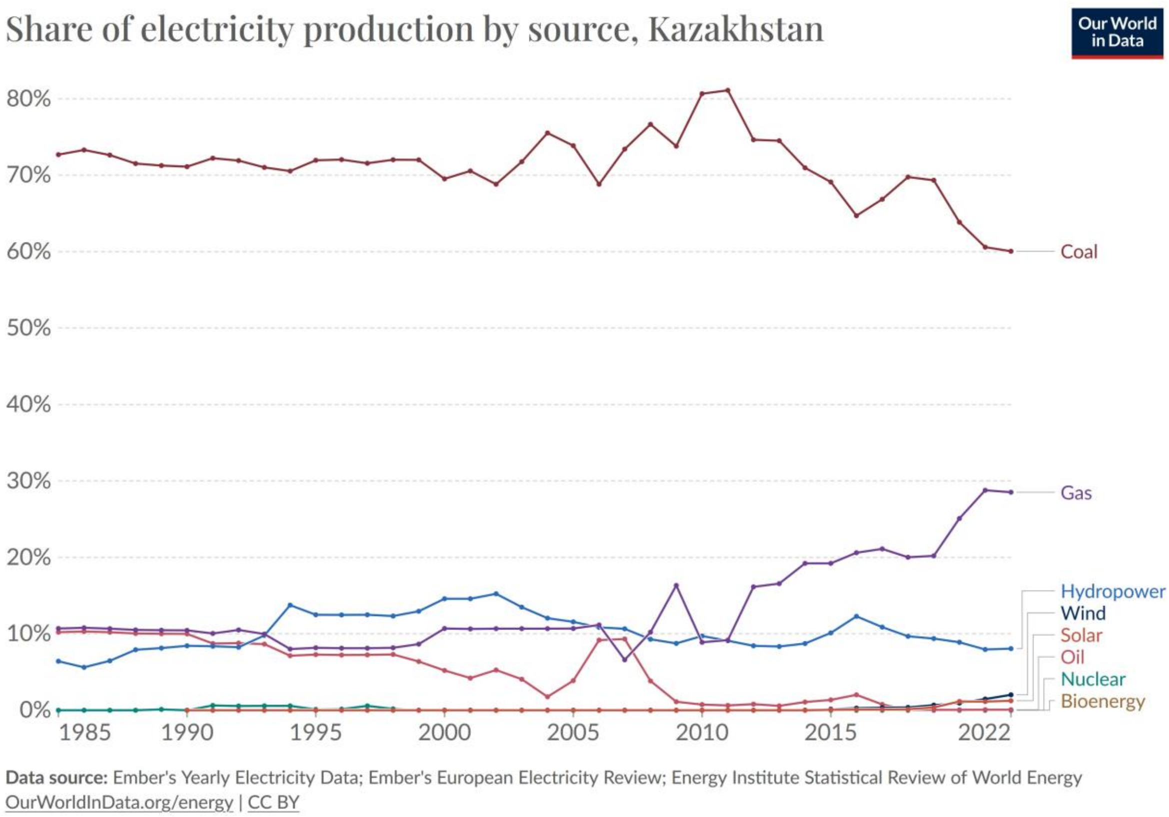
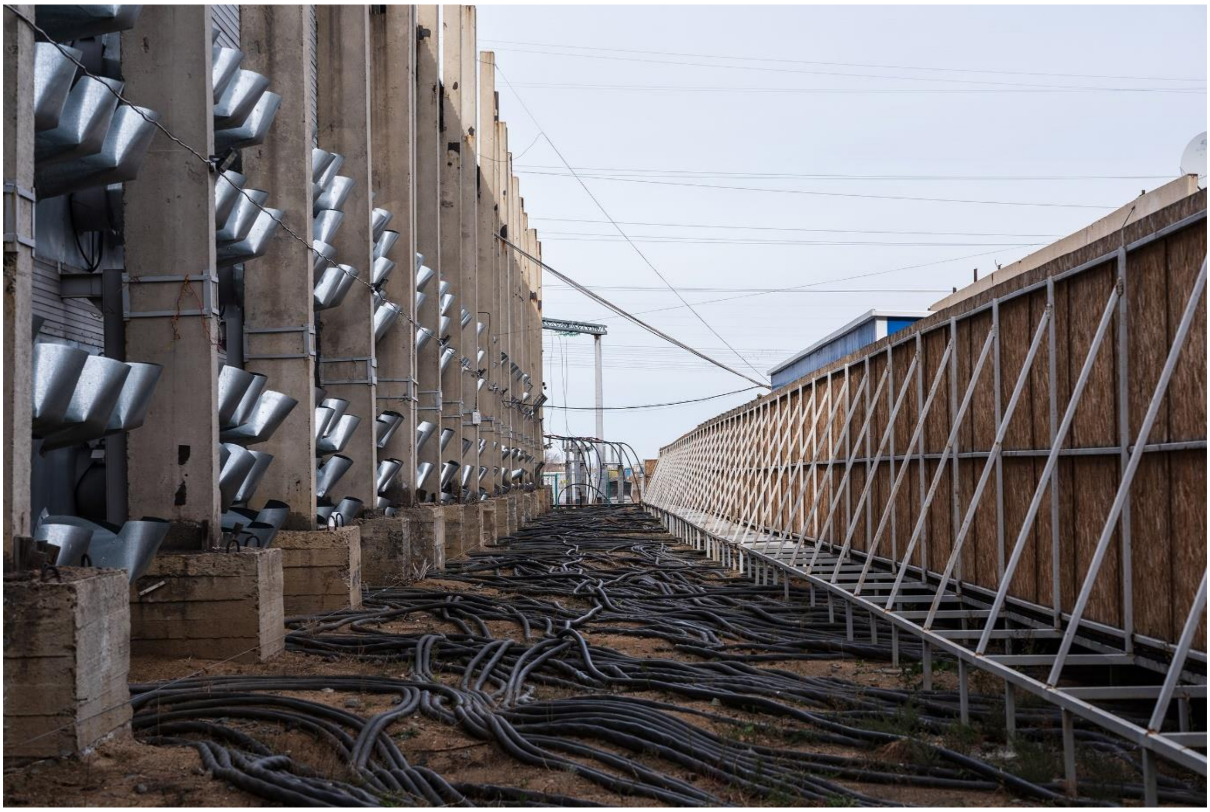


Figure 11: Share of electricity production by source in Kazakhstan



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Notable countries that distinguish themselves with mining activity are Canada (6,48%), Russia (4,66%), Germany (3,06%), Malaysia (2,51%) and Ireland (1,97%). They quotes are however sensibly smaller than the major players of the mining field [95].

Coal and gas are very used in these countries as well, but there are also some high shares of renewable sources as more than 60% of hydropower in Canada, 32% of wind in Ireland and 22% of wind in Germany [98].

4.2 Proof-of-Stake protocol energy consumption

Due to the different nature of the algorithm a simple Raspberry Pi can be used for Proof of Stake protocol, this type of hardware requires 5 W that become a consume of energy of 43.95 kWh annually. This approach consumes a thousand times less energy than Proof of Work for Bitcoin and a hundred times less for Ethereum [107].

However, Proof-of-Stake do not require a specific hardware to validate blocks, so manufacturers are not obliged to produce a dedicated hardware. Any devices connected to the internet can be used [108]. Electric consumption is several orders of magnitude lower than Proof-of-Work [77].

Proof-of-Stake can reach a better settlement that increases blockchain performance and minimizes the mining energy problem [109].

A study that simulates blockchain system has shown that Proof-of-Stakes consensus reduces energy consumption by more than 75% respect Proof-of-Work, the “fairness” however decreases significantly because nodes that have a great amount of coin with Proof-of-Stake have an advantage and they will continue to increase that advantage [110].

Proof-of-Stake protocol was developed to reduce energy consumption, but in doing so the system becomes more centralized and the original nature and purpose of blockchain are betrayed. The question becomes a political and an ethical choice: is it better to consume far less energy or to have a decentralized system free from possible authoritarian control?

Ethereum has chosen to reduce drastically the energy consumption switching to Proof-of-Stake from Proof-of-Work in September 2022 [111]. Proof-of-Stake moreover is also more resistant against cyber-attacks [112].

As can be seen in Figure 13, Ethereum energy consumption has decreased by at least 99,84% after the switch to Proof-of-Stake [113].

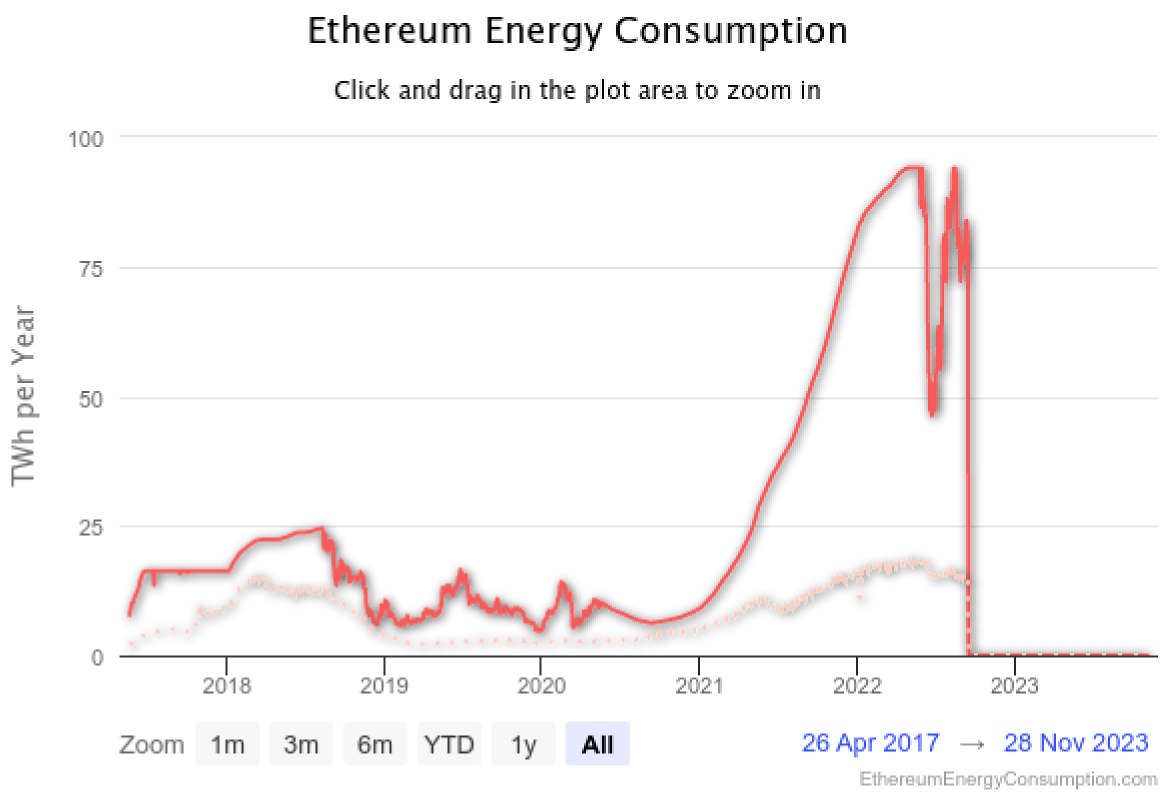

Figure 13: Ethereum energy consumption

4.3 Storage redundancy energy consumption

Storage redundancy is typical of decentralized systems. In a blockchain system each node must store a copy of all system data. Bitcoin volume of data has reached 285 GB in 2020 [18]. Energy consumption increases with the increase of data stored.

In 2023 Bitcoin volume data has reached 530 GB [114], [115].

The energy needed to store a TB is 27.8 kWh per year for information technology (IT) storage devices [116], [117].

The exact number of Bitcoin nodes is unknown, because some nodes can be unreachable for several reasons. They may be configured by the operator to only attempt to make outgoing connections or they may be located behind corporate/ISP firewalls or NAT. A node could also become temporarily unreachable if it has hit its maximum allowed connections or if it is in the process of syncing up to the latest blocks [118]. A current estimation is that there are 17000 nodes in 2023 [119].

With this number of nodes, the 2023 electric consumption for data storage is 250.50 MWh, two orders of magnitude smaller than that of mining.

A way to mitigate the problem is to use lightweight nodes, that store incomplete information and that do not participate in block validation, this remaining exclusive for full nodes. In this way not all nodes must be synchronized and store all data. But again, the true nature of the blockchain system is altered by mitigation strategy for energy saving [18].

5 Results

5.1 Proof-of-Work protocol consumption prevision for Bitcoin

Using Equation (3) future Bitcoin energy consumption related to the mining activity worldwide can be calculated. The estimate starts with 2022 data and goes to 2030 values.

The necessary parameters for the estimation are Bitcoin difficulty, mining hardware efficiency, block mining time and block hashrate [83].

The time necessary to create a new block is constant in Bitcoin protocol and is equal to 10 minutes. For that reason, if the hardware capacity increases so does the block difficulty [83].

Block difficulty changes periodically. The new difficulty is calculated multiplying the old with a correction factor that must be greater than 25% and smaller than 400% compared to the previous one [83]. The evolution of the difficulty during the past years is estimated at [120] and can be seen in Figure 14 (the trend line is also shown).

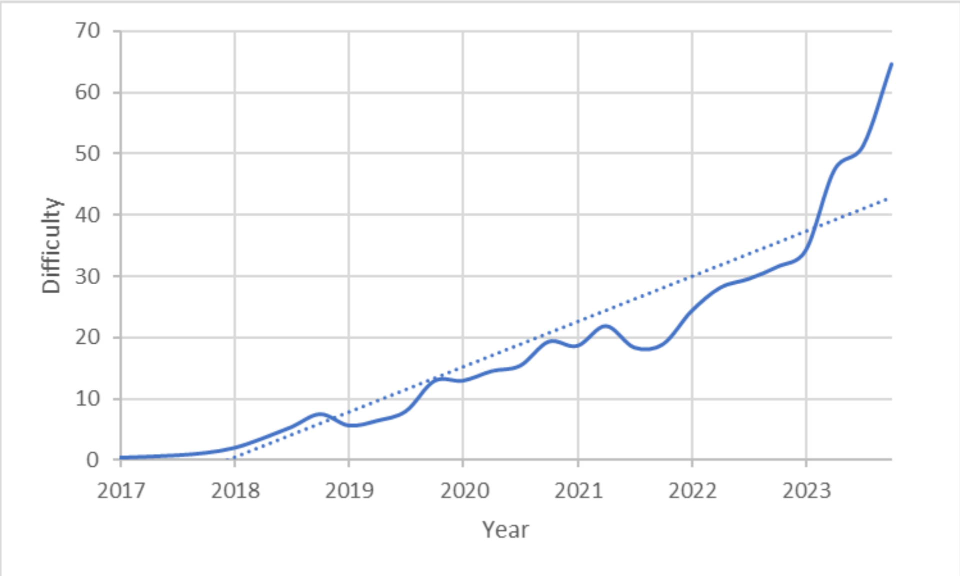

Figure 14: Bitcoin difficulty from 2017 to 2030.

The difficulty raised very slowly in the first years of Bitcoin life, then starting from mid-2018 the increase became more big and almost linear and after 2022 it rose very quickly, almost exponentially to reach the value of 64 in the last months of 2023 [120].

For the hypothetical future trend two scenarios are chosen. A first one that consider the increase from 2021 to 2023 as linear and then continue in that way until 2030. A second that instead starting from difficulty of 64, reached in 2023, follows a linear trend identical to that of the trend line of the past data. The second one as a linear coefficient smaller. They can be observed in Figure 15.

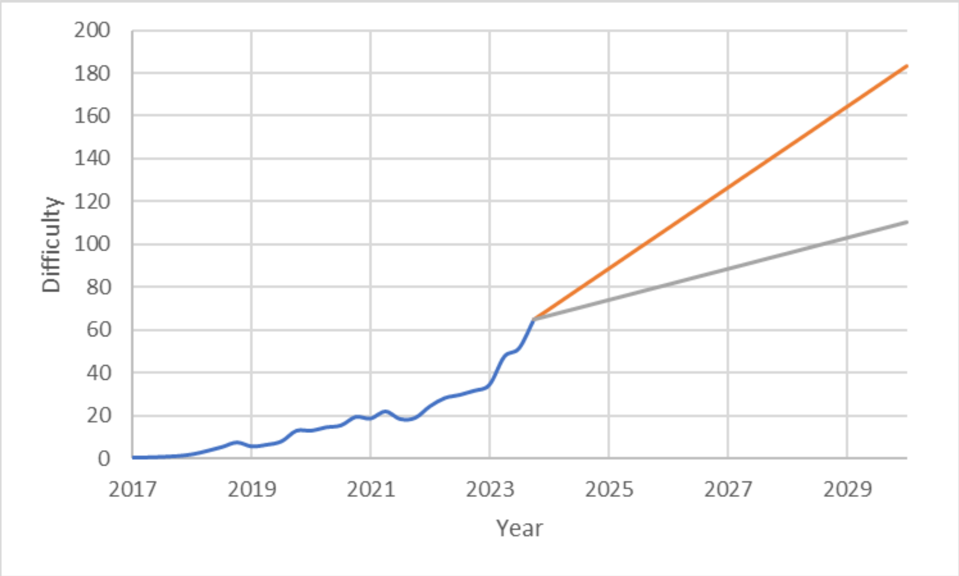

Figure 15: Hypothetical Bitcoin difficulty until 2030: higher difficulty in red, lower difficulty in grey.

In the first scenario (red line) the difficulty increases to almost 180 in 2030. In the second one (grey line) the difficulty becomes instead almost 110 in 2030.

Past data found in the literature show a linear trend for hardware efficiency staring from 2017 to 2022 [83]. This trend has been chosen for the future projection also. The decision is based on the fact that hardware efficiency follows the difficulty trend [83], that has been considered linear for the future, but that has the risk to become exponential, as last recent data show, while hardware efficiency, being connected to hardware production, cannot become exponential.

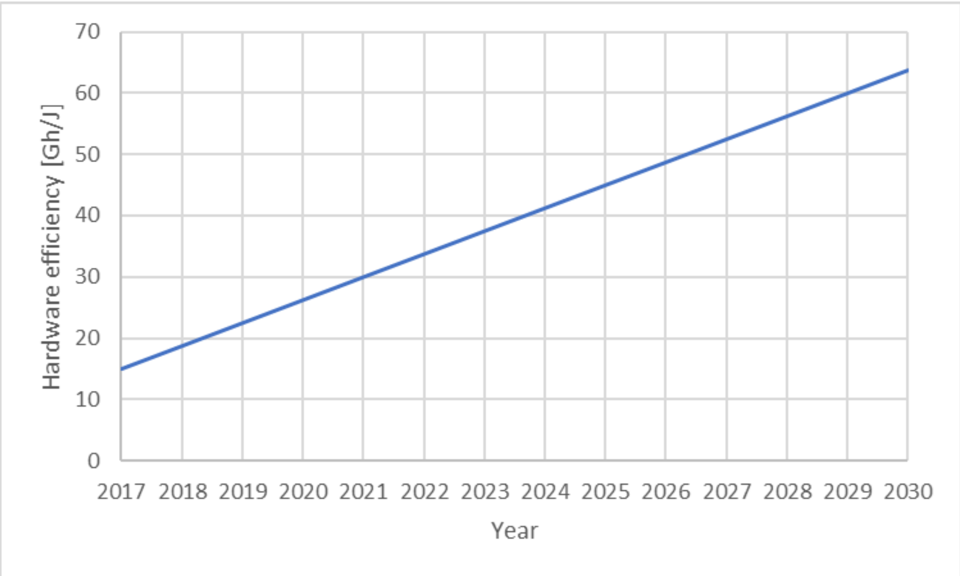

Figure 16: Hardware efficiency from 2017 to 2030.

The efficiency is expressed in Gh/J, where h means hash. From a starting value of 15 Gh/J it arrives to nearly 65 Gh/J.

The hashrate trend can be found again at coinwarz.com [78]. Its trend is like that of the difficulty because there are connected [83]. The historical trend and its trend line are shown in Figure 17. The value reached in late 2023 is nearly 470 Eh/s [78].

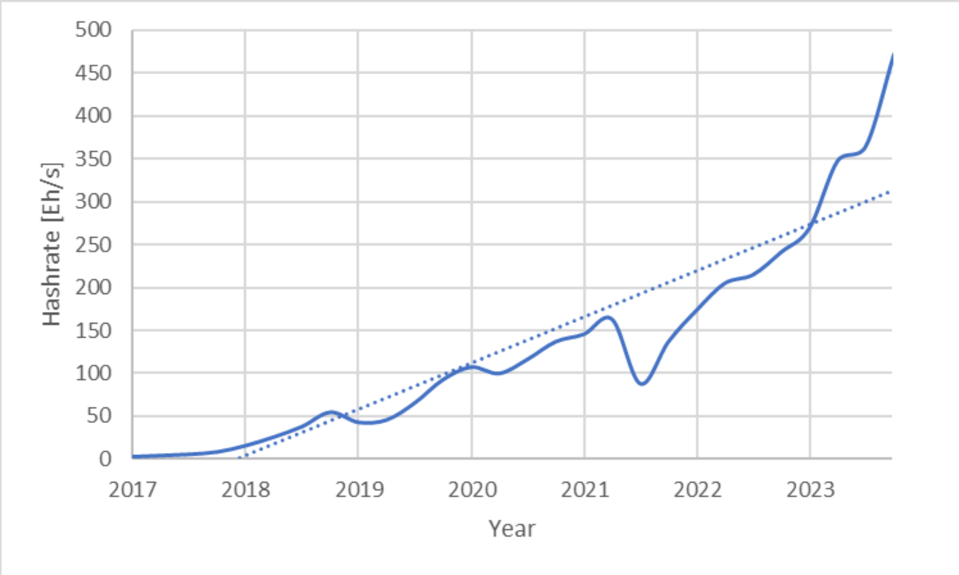

Figure 17: Bitcoin hashrate from 2017 to 2030.

As for the difficulty two future trend scenarios are chosen. A first one that consider the increase from 2021 to 2023 as linear and then continue in that way until 2030. A second that instead starting from the hashrate value reached in 2023 follows a linear trend identical to that of the trend line of the past data. The second one as a linear coefficient smaller also in this case. They are shown in Figure 18 (red line for Scenario 1, grey line for Scenario 2).

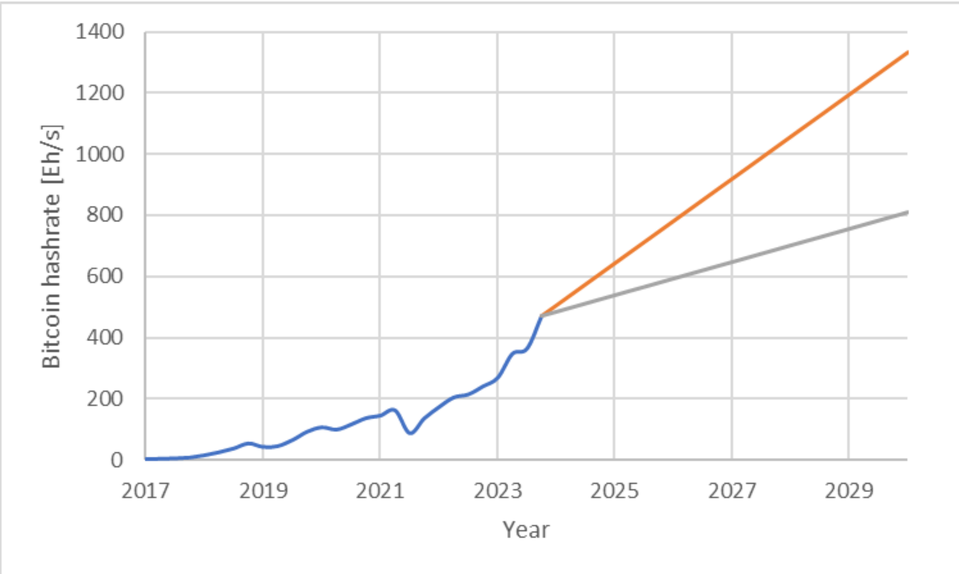

Figure 18: Hypothetical Bitcoin hashrate until 2030: higher hashrate in red, lower hashrate in grey.

Using Equation 3 the power demand necessary for any hash can be calculated and then finally, multiplying it with the hashrate the energy consumption is found.

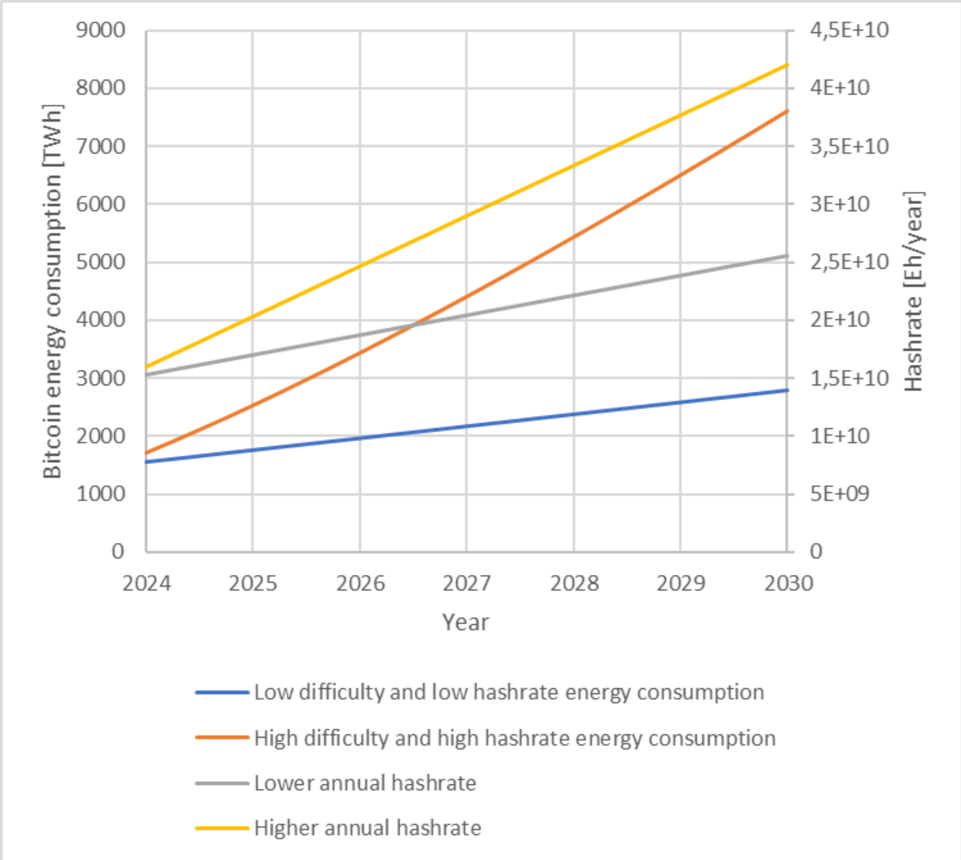

Figure 19: Bitcoin energy consumption and hashrate per year from 2024 to 2030.

Figure 19 shows that the energy consumption increases more than linearly (it is more evident in the scenario with higher difficulty and higher hashrate).

For the first scenario (higher difficulty and higher hashrate) the predicted consumption in 2024 is 1700 TWh and will become approximately 7600 TWh in 2030. The corresponding hashrate per year will increase to $4{,}2\times10^{10}$ Eh/year, corresponding to 42 Qh/year.

The 2021 consumption reported in Table 2 was 135.12 TWh, a value in line with the difficulty trend that started in mid-2021 [120].

If the Bitcoin mining scenario will as in the first scenario, its electricity consumption, that is already similar to that of a small country, will become similar to that of China in 2030, that is actually the most energy expensive country of the World with 8912 TWh of consumption in 2022 [121].

The second scenario (lower difficulty and lower hashrate) has a very similar predicted consumption for 2024 that will become nearly 2800 TWh per year in 2030. The corresponding hashrate will be $2{,}5\times10^{10}$ Eh/year (25 Qh/year).

In this scenario better prospectives for consumptions decrease are shown, but the “Bitcoin nation” will consume in 2030 as much as the European Union has consumed in 2022 (2795 TWh) [121].

5.1.1 Proof-of-Work protocol consumption localization prevision for Bitcoin

Data obtained from the previous simulation of expected consumption (Figure 19) are shown divided by country. The hypothesis is that 2023 mining pools localisation will be the same until 2030, that is a bit unlikely, but to make different previsions is very hazardous in this field that changes very quickly following politic decisions and economic conditions.

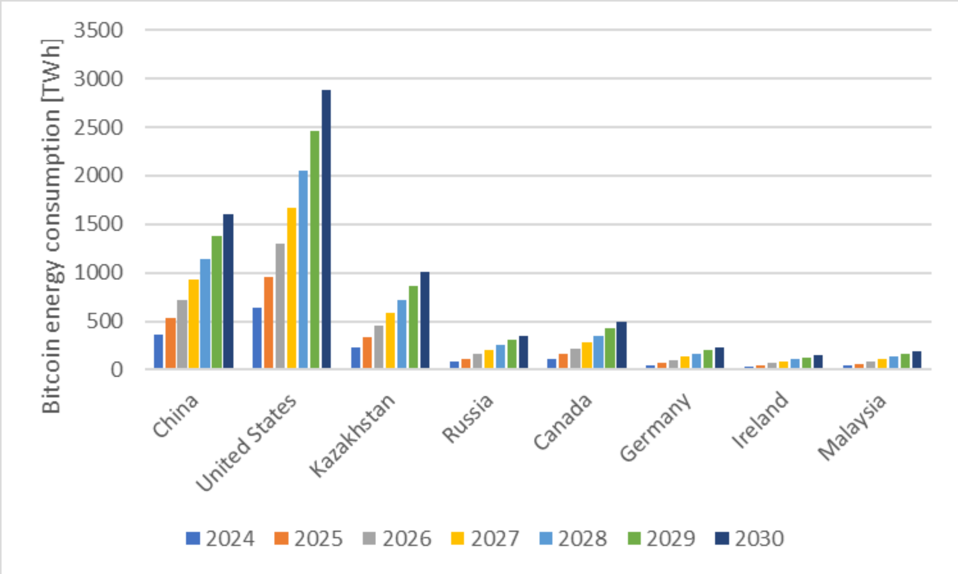

Figure 20: High difficulty and high hashrate energy consumption divided by country.

As can be noticed in Figure 20, Bitcoin electric consumption will arise to value similar to that of big countries for the major player of mining pool industry and to that of smaller countries for the nations with smaller percentages of mining hashrate. In this scenario, Bitcoin energy consumption can be a serious problem.

The United States are the country with greater concerns, because the majority of mining pools are located in US soil. Keeping faith to international traits, the US government has activated legislative vehicles like the Bipartisan Infrastructure Investment and Jobs Act of 2021 and the US Inflation Reduction Act of 2022 to boost clean energy and to reduce greenhouse gas emissions [102], [121]. Considering that actually the residential sector represents the 38.64% of the national electric consumption, the commercial sector the 34.90%, the industrial sector the 26.29% and the transport sector the 1% [122], the not negligible Bitcoin consumption of 2024, greater than 500 TWh/year, that in 2030 will be like the total electric consumption of European Union in 2022, less than 3000 TWh/year, due to the great increase of Bitcoin difficulty, is a great obstacle to all the policies of emission reduction [121] . The actual electric consumption of US is around 4300 TWh/year [98], [121], the industrial sector, that concerns Bitcoin mining activity, is around 1130 TWh/year [122], if in 2030 it will become more or less 3000 TWh/year due to mining activity its increase will be of 265% in less than ten years.

Consumption problems caused by Bitcoin affects China as well; the industrial sector consumes approximately 5600 TWh/year, this value represents the 63.63% of the 8800 TWh/year of all country activities [121], [123], [124]. In 2030 mining activity will require an additional quote of more or less 1600 TWh/year, causing an increase of the industrial sector consumption of 128%. Considering that today 60% of electricity in China is generated from coal power plants, a percentage smaller than the 81% of 2007, proving China great efforts to reduce emissions, mining is a serious obstacle to the fulfilment of Paris Agreement [42], [87], [94], [96], [121]. The modernization of China energy system is a great challenge for the country, coal dependency is a problem difficult to resolve; in 2022 new coal plants have been built for a total power of 90 GW [121]. The 2021 cryptocurrency ban has been an operation in the right direction [93], [100], but since the problem has not been totally resolved, a new stronger legislation against mining will become necessary.

Being the third country for mining pools presence, Kazakhstan also must face energy problems related to mining. With nearly 110 TWh/year of electric consumption [98], of which 33% for the industrial sector (36.30 TWh/year) [125], mining activity, if will evolve as this scenario shows, will be the principal source of electric consumption by far in the country and in 2030 the electricity needed will be approximately ten time that of 2022 (1000 TWh/year). Kazakhstan will have the possibility to use its uranium reserve to sustain this load [106] but a modernization of the energy infrastructure is needed, most of the energy system is still a legacy of the Soviet Union era [105] and the supply grid has weak points that make the country too dependent from Russia [121]. This infrastructural obsolescence causes many problems of local grid overload in mining pools area [105]. To transform the energy system to manage a load ten times greater will be a great effort, that becomes a political problem if this is done only to sustain the trade of a particular type of coin. Kazakhstan has already started to try to decrease mining activity with vacillating results [105].

Data shown in this scenario show very clearly that this trend of consumption evolution is not sustainable, the electricity required for the mining activity is exaggerated considering that it is used for the only purpose to create a particular type of coin. The major players in this field, United States, China and Kazakhstan, will have a great number of problems to manage the energy request of mining pools and above all to complete the transition to a more sustainable energy system. Minor players as Canada, Russia, Germany, Malaysia and Ireland will have similar problems in a lowered way.

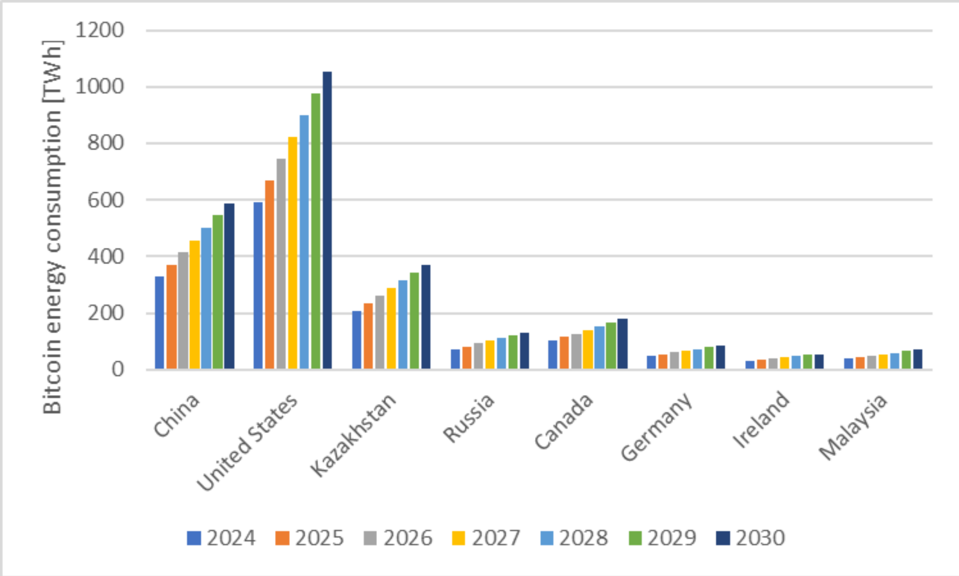

Figure 21: Low difficulty and low hashrate energy consumption divided by country.

In the second scenario the evolution of Bitcoin consumption is less energy-intensive, but the values of the major countries in which mining pools are located are however very high (Figure 21).

The 2024 consumption prevision in United States is similar in both scenarios, approximately 600 TWh/year, but in 2030 in the second scenario will be more or less 1000 TWh/year against 3000 TWh/year. In this case the industrial sector will double its consumption in less than ten years [122].

The second scenario shows a reduction of consumption prevision also in China, starting from 350 TWh/year in 2024 to 600 TWh/year in 2030, with an increase of the industrial sector consumption of 110% caused by mining [123], better than 128% of the first scenario, but still too high for a country very coal dependent [121].

Kazakhstan as well sees a better prospective with the second scenario, with a 2030 prevision of less than 400 TWh/year against 1000 TWh/year. For Kazakhstan, as previously said, Bitcoin mining will be the principal factor of energy consumption of all the country, increasing the total electricity request of five time in more than ten years [125]. In this case as well Kazakhstan will face serious problem in the energy system management [105], [121].

5.2 Proof-of-Stake protocol consumption prevision for Bitcoin

Considering the reduction of consumption by 75% in comparison to Proof-of-Work, a 2024 consumption prevision for Bitcoin can be made [110]. For Proof-of-Work a medium value between the two different scenarios is adopted.

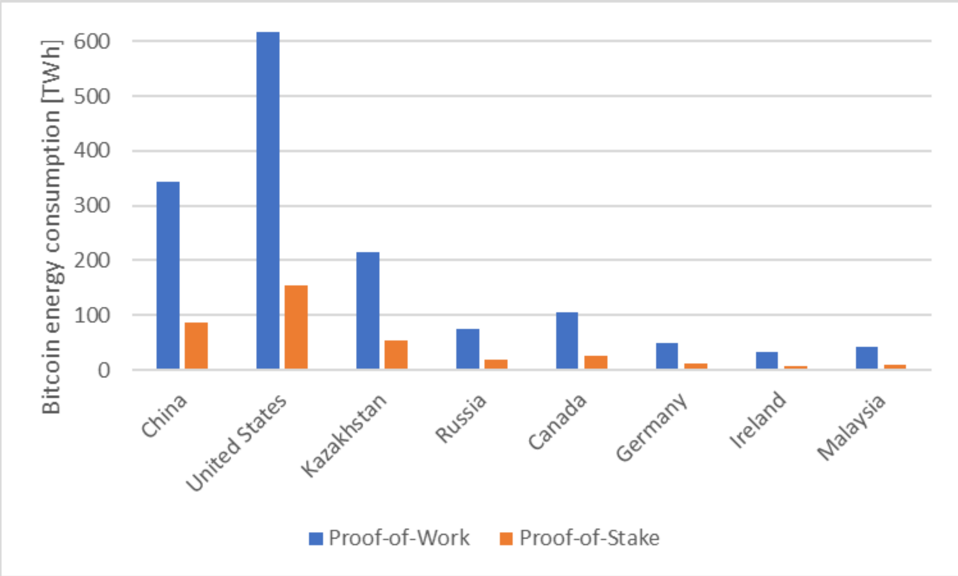

Figure 22: Bitcoin energy consumption comparison in 2024 with Proof-of-Work and Proof-of-Stake.

Figure 22 shows very well the drastic decrease of Bitcoin consumption that will be achieved if Proof-of-Stake will become the protocol algorithm. Worldwide consumption for 2024 will be 405 TWh against 1630 TWh and US consumption will be 155 TWh against 615 TWh.

6 Conclusion

Blockchain was originally born with the only aim to validate Bitcoin (the most famous cryptocurrency) transactions. For that reason, it has been created as a decentralized system with very high cybersecurity qualities.

Through a hashing function a hash value is computed and locally stored inside a block using its content and the hash value of its immediate predecessor. The hash function is created to be very complex to compute, but easy to verify. Each block depends chronologically on the previous one, so the hash value stored at each node cannot be tampered in isolation; this mechanism makes any illegal modification easily identifiable and too computationally expensive. In this way an immutable data storage can be created.

The original protocol created to validate any new block of the chain is called Proof-of-Work. Any node of the system must solve a specific cryptographic puzzle that requires high computational effort; after the validation phase the winner node gains a reward, or a punishment if the block is not valid; in this way an energy-expensive competition is created, and it is regulated via peer control between all system nodes.

Bitcoin popularity has given attention to the blockchain technology. Its characteristics have opened many possibilities for blockchain to evolve in decentralized and public systems as well as in private ones. Different types of block validation protocols have been created to fulfil all the fields of applications in which the blockchain technology has been demonstrate valid to be use. Proof-of-Work, being the first, is still the most used protocol, but alternatives, as Proof-of-Stake, have been developed to contrast the high energy cost that Proof-of-Work requires.

Starting from cryptocurrency transactions, Bitcoin and Ethereum being the most representative, blockchain starts to be used with other instrument as smart contracts, digital ledgers, tokens transactions, that can be used in many fields of applications: cybersecurity, election and voting, healthcare, supply chain, marketing, real estate, mobile, gaming and in the energy sector. In particular blockchain can significantly improve operations in fields as wholesale and decentralized energy trading, with a particular attention in microgrids management, energy management in general, metering and billing and can push a step forward in the use of green certificate and carbon trading and the complex management of the Internet of things and Internet of vehicles.

Having Proof-of-Work the reputation of being an energy-intensive protocol, its energy consumption has been calculated using Bitcoin as case study, being this cryptocurrency the principal blockchain user; Ethereum, the second cryptocurrency for circulation, has switched to Proof-of-Stake, and the other fields of applications are until now very limited compared to cryptocurrencies trading.

Bitcoin difficulty, hardware efficiency and Bitcoin hashrate are used here to calculate present Bitcoin electric consumption and to make future previsions. Bitcoin difficulty is the parameter that characterize the computational effort to validate a new block; hardware efficiency is the efficiency related to the velocity of the block validation; Bitcoin hashrate is the number of block validation per second. Two future scenarios have been described: a first one that follows the trend that both difficulty and hashrate have shown starting from 2021 and a second one in which the two parameters have lower values because they follow the trend line of all the historical data starting from 2017.

All consumptions previsions have also been divided for all the principal countries in which Bitcoin mining pools are located. The major three are United States, China and Kazakhstan, followed by Canada, Russia, Germany, Malaysia and Ireland.

The first scenario predicts a great consumption increase that will reach 7600 TWh/year worldwide in 2030, a value similar to that actual of China, that is the country that consume most energy worldwide. Following this prevision United States in 2030 will consume for Bitcoin trading only as the European Union consumes today (less than 3000 TWh/year). This means that mining activity will increase the electric consumption of US industrial sector of 265% in less than ten years. This is a great obstacle to all the policies of emission reduction for a country that is in first line to implement the energy system in a more sustainable direction. Similar problems are present in China as well; in 2030 mining activity will require an additional quote of 1600 TWh/year, causing an increase of the industrial sector consumption of 128%. China, in comparison to the United States, is in a worse situation regarding emissions because the 60% of electricity is still generated from coal power plants; mining activity will affect precisely China energy system weaker point from a sustainable point of view. Kazakhstan also will have energy problems related to mining that will be the principal source of electric consumption by far in the country. In 2030 it is expected a consume of 1000 TWh/year, ten time that of 2022. Kazakhstan will have the possibility to use its uranium reserve to sustain this load, but a modernization of the old and inefficient energy infrastructure is needed because in the actual condition mining activity stress out all the country grid. Data from the first scenario are very threating to any sustainable policy for energy consumption and emissions reduction.

The second scenario shows better prospectives, with a 2030 prevision in which Bitcoin worldwide consumption is like that of a medium country (2800 TWh/year). The 2030 consumption prevision in United States is 1000 TWh/year against 3000 TWh/year of the first scenario, that means a doubling of the industrial sector consumption in less than ten years. This scenario shows a reduction of consumption prevision also in China to 600 TWh/year in 2030, with an increase of the industrial sector consumption of 110%. Better prospective are shown in Kazakhstan with a 2030 prevision of less than 400 TWh/year against 1000 TWh/year. However also these previsions remain an obstacle to any sustainable development and policies and a problem, although smaller, to the already mentioned inefficiencies of the cited country energy systems.

The solution can be the switch to Proof-of-Stake protocol, that will consent a consumption reduction of 75%, with a global consumption in 2024 of 405 TWh/year against 1630 TWh/year of Proof-of-Work, delivering all cryptocurrency consumption to a reasonable order of magnitude. Proof-of-Stake is a newer protocol and has a bigger margin of improvement from an energetic point of view also.

The blockchain system requires that all its node must save all system data, this redundancy has a surplus energy cost as well compared to other decentralized systems, but this is insignificant compared to the energy cost of the validation protocols.

In conclusion must be said that blockchain has a lot of potential in many fields of application, especially considering that the process of digitalization of goods and services is an increasing trend and one of the goal of the future, but Proof-of-Work is too energy intensive and it represents a serious treat to an other fundamental future goal, that is sustainability, so a solution to decrease consume must be found. The switch to Proof-of-Stake can be a very good option, as Ethereum results show.

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