ENVIRONMENTAL IMPACT OF DIGITAL ASSETS

Crypto-asset mining and DLT consensus mechanisms

OECD

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Crypto-asset markets are rapidly developing and reached USD 3tn in late 2021, yet the infrastructure supporting mainstream crypto-assets, such as the Bitcoin, use an enormous amount of energy. This paper explores the growing environmental impact of crypto-assets due to increasing institutional and retail investors participation in these markets. The use of energy-intensive transaction validation through Proof-of-Work consensus mechanisms and the corresponding carbon footprint create climate transition risks for market participants. Policy considerations and action are necessary given the carbon footprint and associated climate transition risks of certain digital assets when combined with negative externalities extending to the wider society.

Preface

Digital assets are becoming increasingly important for financial markets, with profound implications for market integrity, investor and consumer protection and the stability of the markets. Crypto-assets, such as the Bitcoin, are associated with a significant carbon footprint as they consume enormous amounts of energy - the quantity of which rivals the energy consumption of certain small nations.

The negative environmental impact of the infrastructure supporting some distributed ledger technologies (DLTs), such as the Proof-of-Work consensus mechanism and associated crypto-asset mining underpinning the Bitcoin, call for policy consideration and potential action. The importance of this debate is increasing, as we are witnessing the institutionalisation of crypto-assets such as the Bitcoin that are becoming 'mainstream'. Institutional investors are increasingly participating in markets for such crypto-assets, with their exposures contributing to associated climate transition risks for the financial markets.

The energy demand and environmental impact of crypto-assets, such as the Bitcoin, is particularly important at the current geopolitical juncture. Yet, not all DLTs have the same environmental impact, and there are potential use-cases of DLTs that could support the channeling of financial resources to environmentally-sustainable businesses in a more efficient way.

Given the inherently global nature of digital assets, their environmental impact cannot be curbed if efforts are applied only at the domestic level in some countries and some level of coordination is required at the cross-border level. In the absence of such cross-border coordination, the negative externalities are being transferred from one geography to another, while the overall negative impact to the environment and our societies remains the same.

It is therefore important to achieve agreement about the direction of policy action to limit the negative environmental impact of this emerging activity at the multilateral level. The OECD and its Committee on Financial Markets remain committed to contribute to this effort, by promoting international cooperation and the responsible development and use of emerging technological advances in finance, in a way that supports safe, fair and efficient financial markets.

Yoshiki Takeuchi

OECD Deputy Secretary-General

Foreword

This report examines the environmental impact of digital assets, focusing on crypto-assets and consensus mechanisms of distributed ledger technologies (DLTs) given increased institutional and retail participation in these markets. It examines the differences in carbon footprint of different consensus mechanisms and underlines the lack of reliable data evidence around the carbon footprint of the different crypto-asset activities and consensus mechanisms. The report explains why the use of renewable energy is not sufficient to curb the negative externalities and highlights the importance of international cooperation and coordination in policy action around crypto-asset mining, before putting forward policy considerations.

The report has been drafted by *Iota Kaousar Nassr* under the supervision of *Robert Patalano* from the Division of Financial Markets of the OECD Directorate for Financial and Enterprise Affairs. *Edward Keunuk Shin* provided research assistance and *Liv Gudmundson* provided editorial and communication support.

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Executive summary

Digital assets[1] have increasingly gained interest from financial markets participants and citizens given the rapid development of crypto-asset markets, which reached USD 3tn as of end of 2021. In parallel, environmental, social, and governance (ESG) factors have risen to become a priority for policy makers, and there is greater societal awareness of the urgent need for action on climate and sustainability issues.

The infrastructure supporting crypto-assets, such as the Bitcoin, uses an enormous amount of energy, the quantity of which rivals the energy consumption of certain small nations. In 2021, Bitcoin was responsible for 65 Mt CO_2 of emissions per year representing 0.2% of global emissions, greater than the carbon footprint of entire nations, while a single transaction of Bitcoin that year had on average the same carbon footprint as a single seat does in a passenger flight from Amsterdam to New York (670 kg CO_2) (de Vries et al., 2022[1]). The use of renewable energy is not sufficient to curb the negative externalities given the opportunity cost for the use of renewables elsewhere in society. The use of temporary excess renewable energy generation is not a credible alternative either, as excess generation – temporary by nature – does not match the 24/7 demand for energy of Bitcoin mining.

Reflecting institutional and retail investor demand for crypto-assets, more scrutiny is warranted across all aspects of this market, including its environmental impact. Proof-of-Work (PoW) consensus mechanism for the validation of transactions and associated crypto-asset mining are the key drivers of carbon footprint of blockchain-based finance. There are doubts as to whether the Bitcoin could transition to alternative, less energy-intensive validation mechanisms – similar to what the Ethereum blockchain has done –given that it is a highly decentralised network, with the community of participants showing less willingness to make such a transition. As such, alternative policy action may need to be taken.

The use of energy-intensive transaction validation using Proof-of-Work consensus mechanisms and the corresponding carbon footprint creates climate transition risks for market participants. It can undermine the progress of climate transition and may not be correctly priced in, especially given the possible lack of awareness of such footprints by some of the holders and the lack of robust data about the measurement of such impact. This consideration is most relevant to professional and institutional investors as high-carbon emission assets may be incompatible with their ESG objectives and their shift towards a low carbon transition. Attention to this issue is expected to increase as crypto-asset markets and traditional financial markets become more interconnected.

Given the carbon footprint and associated climate transition risks of certain digital assets, combined with negative externalities extending to the wider society, policy consideration and potential policy action is warranted. Outright banning of crypto-asset mining activity may not be the most effective solution to address these risks given the risks of displacing or concealing such activity instead of curbing it, as was the case with the China ban of crypto-asset mining in 2021. Restrictions could be considered on the type of energy sources used for such activity (e.g. energy mix specifications concerning stranded renewables, or a ban of the use of fossil fuel for crypto-asset mining). Focused effort on those specific types of

[1] Digital assets for the purposes of this report include crypto-assets, stablecoins and decentralised finance or DeFi.

blockchains with the greater negative impact would prevent any unintended consequences for the development of DLT innovation that can have potential benefits for the markets and the economy. Such potential benefits may also extend to the use of DLT innovation to promote the efficient channelling of funding towards sustainable finance (e.g. tokenised green bonds).

Currently, the lack of high quality, consistent data about the environmental impact of digital assets is a major hurdle to any informed policy discussion and possible action. There is a large divergence in data estimates depending on methodologies and assumptions used, and it is therefore important to close the data gaps in this area. The possible introduction of disclosure requirements, coupled with industry-led initiatives for improved transparency may alleviate such impediments.

As with all aspects of digital asset policy making, the environmental impact of such assets cannot be addressed if efforts are applied only at the domestic level in some countries. This was evident in the case of China's ban of crypto-asset mining, which resulted in (a) the relocation of miners to other geographies with the same net effect for the globe; and (b) the concealing of activities still operating in China through the use of technical means. Given the inherently global nature of digital assets and markets, some level of co-ordination needs to be encouraged at the cross-border level. In the absence of such cross-border co-ordination, the negative externalities are being transferred from one geography to another, while the overall negative impact to the environment and our societies remains the same.

1 Environmental impact of DLT infrastructures

The decentralised nature of DLTs is made possible, in part, by the consensus mechanisms used to determine the state of the blockchain data, which replace centralised authorities or a single party as record-keepers in centralised systems. The consensus mechanism is therefore a key component of every blockchain that ensures participants are working based on the same ledger containing the same set of historical transactions and according to the same rules. In particular, new blocks are only added to the chain if the participants in the blockchain network have reached consensus over the validity of the transactions and their sequence. The consensus mechanisms incentivise and enable participants of the blockchain network (nodes) to reach a common agreement, while preventing participants from acting maliciously or prioritizing their own interests above those of the network (see also Box 1.1).

This section looks at the different mechanisms that have detrimental impact on the environment and reviews the literature about the measurement of such impact. Identifying environmentally harmful types of blockchain-related mechanisms is crucial so as not to stifle innovation for the entire DLT sector, and quantifying the environmental impact of such activity will be important for any informed policy discussion and possible action.

1.1. Not all blockchains are the same: Proof-of-Work consensus mechanism and crypto-asset mining

Consensus mechanisms differ across blockchains, and so does their corresponding environmental impact. Proof-of-Work (PoW), which underlies the Bitcoin blockchain, constitutes the most energy-intensive validation mechanism in the DLT space. PoW was the earliest type of consensus mechanism to validate crypto-asset transactions; however, DLT energy use was not a prominent consideration when the Bitcoin white paper was first published (Nakamoto, 2008[2]). Purposely making Bitcoin energy intensive was actually a key part of the white paper. The economics of Bitcoin require mining to be expensive, and high energy demand as well as intentional inefficiencies serve this function. Notably, the fixed block size and block time of Bitcoin have not helped the Bitcoin blockchain fulfil its initial stated purpose as a payments base layer, as the speed of transactions and the related scalability limitations have prevented Bitcoins from becoming a medium of exchange (Fatas, 2019[3]; Hinzen, John and Saleh, 2022[4]). Instead, Bitcoin became a speculative investment asset, and its popularity led to the proliferation of 'crypto-asset mining' activities on the PoW network that underlies Bitcoin, which has incentivised the acquisition and operation of powerful mining hardware.

The Bitcoin blockchain relies on the energy-intensive process of ‘mining’,[2] which involves the use of aggregated computing power to participate in the mechanism that determines what is recorded on a blockchain. Transactions are validated and recorded as long as the majority of the computing power agrees, and in order to validate and record transactions, participants have to compete to solve complicated mathematical puzzles. More powerful computing hardware enables a higher likelihood of solving the puzzles before other network participants but may consume a correspondingly larger amount of energy. As an incentive for consuming CPU[3] time and electricity to support the network, mining participants are rewarded with new coins and transaction fees.

Box 1.1. Why do we need consensus mechanisms in blockchains?

The Bitcoin blockchain, the first blockchain introduced in 2008, designed a value transfer system that allows users to transfer digital units (Bitcoins) in a peer-to-peer manner without the involvement of traditional intermediaries. In its technical innovation, the Bitcoin blockchain provided solutions to two core problems of distributed computing:

The Byzantine Generals Problem, which in the context of DLTs describes the problems of establishing a secure and trustworthy exchange of messages in a network of unknown participants, which cannot be trusted ex ante; and the Double Spending Problem. The latter arises from the potential for a digital unit of account to be infinitely reproduced and spent repeatedly. In the absence of a central authority monitoring the state of the network and distribution of Bitcoins, the Bitcoin blockchain prevents double spending of coins by providing a central ‘clock’ to validate the correct sequence of transactions.

The consensus mechanism is a set of rules that define what a transaction consists of, and what constitutes a valid transaction. Consensus mechanisms are designed with an incentive system at their core to economically secure the blockchain by fostering network participation. The consensus algorithm decentralises control of the blockchain by forcing participants in a P2P network to co-operate in enforcing the consensus rules.

A third important reason for the existence consensus mechanisms is that these also introduce an expense on miners/ validators, and it is necessary that this be expensive to dis-incentivise falsification. There must be, by design, high up-front costs (either in the form of staking or mining). As such, the energy expenditure of PoW consensus mechanisms is a feature of the system, and not a bug.

Source: Nakamoto (2008[2]), Bitcoin: A Peer-to-Peer Electronic Cash System, www.bitcoin.org.

The profile and geographic location of crypto-asset miners has been evolving. Tech enthusiasts and hobbyists could individually mine Bitcoin on their personal computers in the earliest days of Bitcoin mining (2009-11). Expensive specialised hardware was developed, which limited the possibilities of profitable mining as a hobby. Miners congregated in parts of the world that offered low-cost electricity, a regulatory-friendly environment, a stable political situation, reliable internet connectivity, and in some cases a cold climate to reduce the expense of cooling processing equipment. During 2017-18, mining was concentrated in North America (USA and Canada), Northern and Eastern Europe (Russia, Georgia, Armenia, and

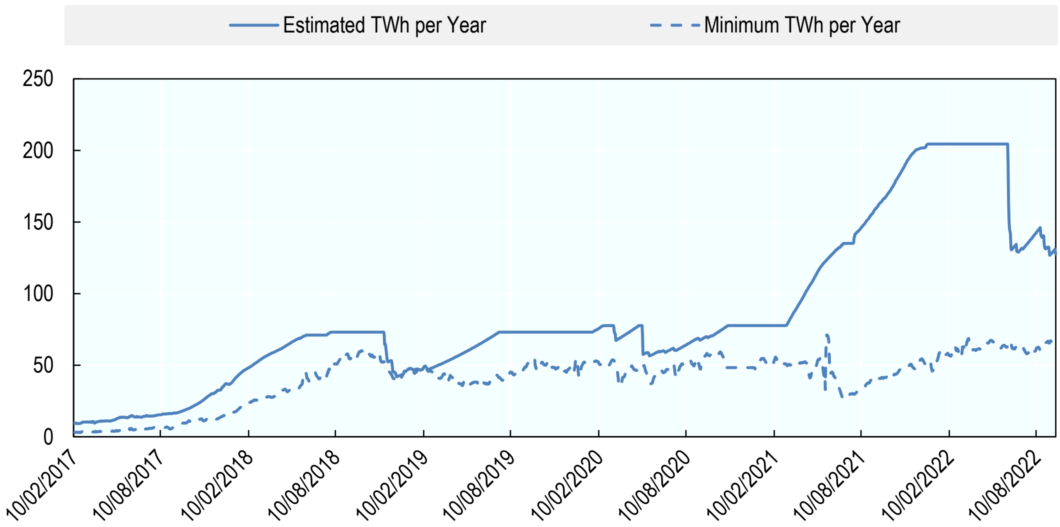
[2] Nakamoto described this process to be analogous to gold mining, and the crypto community soon referred PoW and other consensus mechanism as ‘crypto-mining’, since it is comparable to miners spending resources to acquire valuable minerals (Calvão, 2019[59]).

[3] In practice, CPUs (and GPUs) have not been viable in mining Bitcoin for years due to energy costs exceeding possible revenue. ASIC (Application Specific Integration Circuit) is the most recent and current crypto-asset mining infrastructure.

Sweden), China, and Australia (Rauchs et al., 2018[5]). China banned crypto-asset trading and mining in 2021 over environmental concerns, leading to relocation of mining activities to other parts of the world such as the US and Kazakhstan, places that offered affordable energy sources (Bloomberg, 2022[6]).

There are several reasons why crypto-asset mining uptake has been high but the primary and dominating driver of such activity is the financial rewards. Financial motive is one of the primary motives for miners and investors alike (Blandin A. et al., 2020[7]; Fang et al., 2022[8]). This is in line with the motivations of the vast majority of those involved in markets for crypto-assets, who are drawn into these markets for speculative reasons (OECD, 2022[9]). The growth of the crypto-asset ecosystem over the past five years has provided ample financial incentives that attracted an increasing number of miners since the inception of Bitcoin in 2009. More than 12 000 alternative ('alt') coins have been introduced, with hundreds of them still in circulation (TheMotleyFool, 2022[10]). Besides financial incentives, DLT-based systems such as Bitcoin present opportunities for illicit actors, given their pseudonymity. Tech-enthusiasts and crypto-asset 'anarchists' have ideological reasons for engaging in this activity.

Figure 1.1. Total energy consumption of the Bitcoin network



Source: https://digiconomist.net/Bitcoin-energy-consumption

Crypto-asset mining financial returns correlate with crypto-assets' market prices. Mining revenues consist of the sum of transaction fees paid to miners, plus the market value of newly minted coins awarded to miners who successfully compete to record transactions to the blockchain. Holding all else equal, Bitcoin mining firms' profit margins increase when the price of the underlying crypto-asset increases, and therefore mining activity – and the corresponding energy consumption – is expected to be greater when the price of the underlying crypto-asset increases.[4] The trend in financial rewards from mining can be used to predict short term direction of the energy use of the network (de Vries, 2021[11]). Empirical evidence suggests that Bitcoin prices correlate with mining revenue per transaction (CME Group, 2022[12]), revenue per hash-rate[5] growth (Compass Mining, 2022[13]), and hash-rate (Kamiya, 2019[14]). It should be noted, however, that

[4] Song and Aste (2020) finds that Bitcoin's lower estimation of the mining cost per transaction remained stable from 2010 to 2020. This phenomenon occurred despite a 10 billion-time increase in mining activities and a near 9 000-time improvement in mining hardware efficiency.

[5] Hash power represents the computing power of the network.

network congestion can drive up the variable transaction fees that miners also receive, while hash rate growth is also linked to a more general trend in ASIC miner development.[6]

Although crypto-asset mining is often compared to commodities mining, crypto-asset mining does not produce efficiencies from advances in mining tools in terms of lower environmental costs. The increase in computing power leads to the increase in the environmental impact, yet greater computing power by design does not lead to additional crypto-assets minted[7] (Hougan M. and Lawant D., 2021[15]). This contrasts with the characteristics of commodities mining, wherein advanced mining tools and operations lead to more resources extracted for society.

1.1.1. E-waste associated with crypto-asset mining infrastructure and hardware

Crypto-asset miners use dedicated infrastructure for mining, and such mining tools need to be constantly replaced to keep up with powerful computing hardware (Sai et al., 2021[16]), with an associate electronic waste (e-waste) impact when mining hardware becomes obsolete.[8] Greater relative computing power leads to greater rewards, which naturally escalates an "arms race" in mining hardware (Hinzen, John and Saleh, 2022[4]). As mining infrastructure evolves, the nature of the miners also is evolving. Initially, individual miners' using personal computing equipment was sufficient, but they were eventually replaced with investor-funded mining start-ups.

Competition for powerful mining infrastructure led to centralised mining operations (Becker et al., 2013[17]). Furthermore, higher concentrated mining operation enjoyed economies of scale and a greater market share (Maurer, Nelms and Swartz, 2013[18]; Castor, 2022[19]). In parallel, as the mining infrastructure evolved, crypto-asset miners increasingly adopted ASICs, which are superior to general computing hardware at processing crypto-asset transactions (Cho, 2018[20]). Given the specialised nature of ASIC, there were only a few ASIC manufacturers, leading to centralised distribution of mining infrastructure (Reiff, 2021). ASIC infrastructure and centralised mining operations may have led to relatively greater energy efficiency, but they have exacerbated the environmental impact.

It is important to note that technology improvements in mining hardware do not reduce the environmental footprint of a PoW network, particularly given the constant miners' race and consequent increase in computing power. Although a more efficient mining hardware decreases electricity consumption, under a scenario of the same mining revenue and lower mining costs, there is an increased likelihood of miners adding computing power to maintain an advantage over other miners. Soon, competitive miners will improve their infrastructure to increase their mining capacity and compress margins. Hardware improvements can lead to temporary decreases of electricity consumption, but they will soon be offset by the addition of computing power that requires more electricity.

[6] The amount of computational power per unit of energy consumed has more than doubled every 1.5 years since ASICs were released (i.e. hash rate may go up even if the price remains stable).

[7] The Bitcoin protocol adjusts the difficulty of the mathematical puzzle that needs to be resolved by miners, so that a new block on its distributed ledger is added approximately every 10 minutes.

[8] For studies on hardware development in Bitcoin mining see (Taylor, 2017[21]) (Vranken, 2017[23]); (de Vries and Stoll, 2021[36]); (Stoll, Klaaßen and Gallersdörfer, 2019[28]); (Kamiya, 2019[14]).

Box 1.2. The evolution of hardware used for crypto-asset mining

CPUs (Central Processing Units) were the first computing hardware devices used for Bitcoin mining. They process and execute instructions in electronic devices (examples: computers, mobile phones, and tablets). CPUs can be thought of as the "general purpose" brains of computers. Due to their general purpose nature, CPUs can conduct a range of computational tasks, but they are less powerful than other specialised hardware at performing specialised tasks such as crypto-asset mining. Early Bitcoin mining required relatively low computing power, so miners could validate Bitcoin transactions using CPUs.

GPUs (Graphics Processing Units) were the second generation of Bitcoin mining hardware. They are similar to CPUs, but they focus on graphics processing. Compared to CPUs, GPUs excel in repetitive mathematical operations, which enable efficient graphics processing. Similarly, crypto-asset mining relies on solving complicated mathematical puzzles. Miners recognised the potential of GPUs over CPUs, and soon reprogrammed GPUs for Bitcoin mining.

FPGA (Field Programmable Gate Array) was a short-lived mining hardware. An FPGA is a type of electronic circuit that can be adapted to the specific needs of the users. Although FPGA configuration is relatively difficult, it is more efficient and powerful than the previous generations of mining hardware.

ASIC (Application Specific Integration Circuit) is the most recent and current crypto-asset mining infrastructure. As its name implies, it is a type of electronic circuit that is built for a single specialised task. It can be built to mine crypto-assets, but it can only mine crypto-assets that rely on the same underlying algorithm to verify transactions. For example, an ASIC developed for Bitcoin mining could not be used for mining any other type of crypto-asset. Miners adopted ASIC due to its advantage over the previous hardware at mining their targeted type of crypto-assets, but the single-purpose nature of ASIC has led to huge volumes of electronic waste (de Vries, 2021[11]).

Source: Taylor (2017[21]), The evolution of Bitcoin hardware, https://michaeltaylor.org/papers/Taylor_Bitcoin_IEEE_Computer_2017.pdf.

Improvements in the mining hardware and consequently higher computing power will not enhance the transaction process, due to design of the Bitcoin protocol. The Bitcoin protocol is designed so that one block can be added to its blockchain every ten minutes. If the network's hash rate changes, then the computational difficulty of adding the block will be adjusted accordingly. The difficulty adjustment is directly proportional to the hashing power of miners. A Bitcoin block is 1 megabyte; a fixed block size means that if the rate of block creation is held constant, as is the case, then the miners can process a limited number of transactions regardless of technological advancements in mining infrastructure. Therefore, an advance in hardware does not provide benefits with regards to transaction volume, speed nor energy consumption.

1.1.2. Energy consumption for transaction validation vs. mining

One important distinction that needs to be made is between energy consumption for transaction validation and energy consumptions for crypto-asset mining: it is the mining process, and not the transaction validation, that consumes most energy in the Bitcoin network (Carter, 2021[22]). In other words, there is a limited marginal effect from processing more transactions on the Bitcoin blockchain, as the transaction capacity is capped (but the energy consumption is not).[9] Moreover, the issuance of mining rewards decreases over time by design of the Bitcoin protocol; approximately 90% of Bitcoin has already been

[9] Transactions are only processed once they have been added in a new block to the blockchain and one new block is validated every circa ten minutes.

minted. At present, miners receive small fees for the transactions they verify, accounting for approximately 10% of miner revenue (Carter, 2021[22]).

The built-in economics of the Bitcoin protocol create a natural limit to mining rewards and the ensuing drivers for such activity. In particular, the protocol is built to halve the number of newly minted Bitcoins every four years. This means that, unless the price of Bitcoin doubles every four years in perpetuity, the share of miner revenue from newly issued coins expressed in fiat currency will eventually erode to zero (Carter, 2021[22]).

1.2. Quantifying the environmental impact: absence of consensus and lack of solid data evidence

There is no reliable consensus about the environmental cost of crypto-asset mining given the difficulty in accurately estimating the carbon footprint of crypto-asset mining activities (Vranken, 2017[23]; Zimmer, 2017[24]).[10] Empirical studies providing one of the earliest estimates of the environmental impact of Bitcoin, suggested that Bitcoin alone could push global warming above 2°C (Mora et al., 2018[25]). Such studies were followed by rebuttals questioning the assumptions used in the analysis, and even the rebuttals were, in turn, disputed.

The divergent estimates of the environmental cost are attributed to a large extent to inadequate crypto-asset mining data. The Bitcoin Mining Map produced by the Cambridge Centre for Alternative Finance shows global distribution of hash-rate, which approximates energy consumption, but is also based on specific assumptions (CCAF, 2022[26]; Krause and Tolaymat, 2018[27]). The methodology of the Bitcoin Mining Map includes three assumptions that reflect the difficulties of accurate estimation due to data sparsity. However, those assumptions may not be accurate. First, Internet Protocol (IP) address of the miners may not be an accurate reflection of their physical location. Because of external circumstances such as crypto-asset mining regulation, some miners may use a Virtual Private Network to mask their locations. There is no reliable data to adjust for this, except for local outages that may allow for validation of regional shares – although these are extremely rare events (de Vries et al., 2022[1]). Second, data provided by the mining pools may not accurately reflect all miners. As of 2022, the Cambridge Centre collects data from miners accounting for less than half of the total hash-rate of Bitcoin, so one cannot be certain that the sampled data is sufficient to estimate the entire population. The third assumption is related to the second, except on a provincial level in China.

Table 1.1. Estimates of the evolution of electric power used for crypto-mining

Study	Study period	Crypto-asset	Annual electric power	Hardware inclusion
Vranken, 2017	2014–16 (publication of the 3 studies reviewed[1])	Bitcoin	100-500 MW	No
Stoll et al., 2019	2016	Bitcoin	345 MW	No
Stoll et al., 2019	2017	Bitcoin	1.637 GW	No
de Vries, 2018	2018 March (Theory)	Bitcoin	2.55 GW	Yes

Note: 1. 2014to 2016

[10] Only the minimum is considered by academics easy to determine with a high degree of confidence.

Source: Vranken (2017[23]) Sustainability of bitcoin and blockchains, 10.1016/J.COSUST.2017.04.011 ; Stoll et al. (2019[28]) The Carbon Footprint of Bitcoin, 10.1016/J.JOULE.2019.05.012 ; de Vries (2018[29]) Bitcoin's Growing Energy Problem, 10.1016/J.JOULE.2018.04.016 .

Another source of divergent estimates of crypto-asset mining activity is the different assumptions made to estimate the environmental impact (Gallersdörfer, Klaaßen and Stoll, 2020[30]). For example, studies assign values for the carbon footprint and electricity cost per unit of crypto-asset minted, but actual values can fluctuate over time and by location. The IP addresses of mining nodes are assumed to be accurate, but they are easily modifiable, so that it is impossible to know the location of the node in a Bitcoin network (de Vries, 2018[29]). Mining data is assumed to be representative, but there may be differences in the characteristics of miners voluntarily reporting data and those who do not. Indeed, miners are reported by media sources to sometimes conceal their operations, making it difficult to identify and collect the representative data (CCAF, 2022[31]). Mining hardware is also assumed by some of the academic studies referred to above to be up to date, but in reality the mining infrastructure is heterogeneous. Also, some of the academic studies assume that miners pay residential prices for electricity, when in reality most miners pay preferential electricity prices (Blandin A. et al., 2020[7]). Some studies incorporate renewables as a source of energy, but the proportion of renewables fluctuates seasonally. Moreover, studies may consider the grid average energy mix and emission factors, but do not capture typical grid dynamics in which renewables tend to get dispatched first; that means that an increase of demand as a result of miners settling in a certain location may primarily trigger the marginal (fossil fuel-based) power resources. This effect has not been studied in the context of Bitcoin mining and may therefore mean that such studies are understating the carbon footprint of the network (de Vries et al., 2022[1]). Although published studies are based on reasonable assumptions, data limitations and heterogeneity as well as fluctuating electricity costs and the proportion of renewables in energy generation can be beyond the researchers' access, leading to a range of estimations.[11]

It should be noted, however, that the energy consumption of the Bitcoin network does not equate to the carbon footprint, which incorporates the energy mix of the energy used. The exact sources of energy used are critical to calculate the carbon footprint, and to that end, the use of renewables is suggested by the crypto-asset mining industry as a way to partly address the environmental impact of mining (see Section 2.4). As of the writing of this report, there is no evidence of the switch to renewables actually happening.

Table 1.2. Evolution of carbon emission estimates from crypto-asset mining

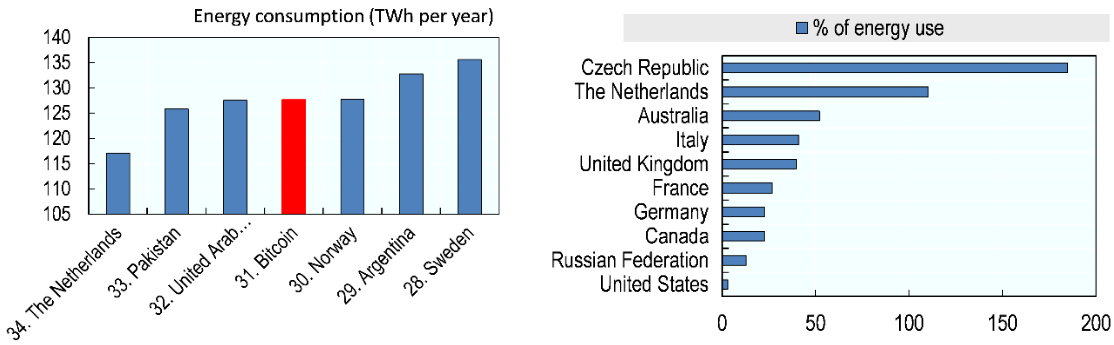
Study	Study period	Crypto-asset	Annual emission	Emission per transaction	Hardware inclusion
Stoll et al., 2019	2018	Bitcoin	22 to 22.9 Mt CO_2 (51 Mt CO_2, if no renewables were used)		No
de Vries et al., 2022	2021	Bitcoin	65.4 Mt CO_2	669 kg CO_2	No
Foteinis, 2018	2018? (author does not specify the study period)	Bitcoin and Ethereum	43.9 Mt CO_2 (ReCiPe and IPCC 2013 methods)		No
Krause and Tolaymat, 2018	2016 January – 2018 June	Bitcoin	3–13 Mt CO_2 (over 1.5 years)		No
		Ethereum,	0.3–1.6 Mt CO_2		

11 For example, (Dittmar and Praktiknjo, 2019) finds that Mora et al. (2018) Mora's electricity consumption is 7 to 14 times greater than other estimates, and (Masanet et al., 2019) finds it 4 times greater. Consequently, the initial CO_2 value is roughly overestimated by a factor of 4.5 (Houy, 2019; Masanet et al., 2019). The main difference was that Mora et al. generally held current conditions fixed while the other authors did not.

		Litecoin, and Monero	(over 1.5 years)		
Trespalacios and Dijk, 2021	2020	Bitcoin	45 Mt CO_2	402 kg CO_2	No

Source: Stoll et al. (2019[28]) The Carbon Footprint of Bitcoin, 10.1016/J.JOULE.2019.05.012 ; de Vries et al. (2022[32]) Revisiting Bitcoin's carbon footprint, 10.1016/J.JOULE.2022.02.005 ; Foteinis (2018[33]) Bitcoin's alarming carbon footprint, 10.1038/D41586-018-01625-X ; Krause and Tolaymat (2018[27]) Quantification of energy and carbon costs for mining cryptocurrencies, 10.1038/s41893-018-0152-7 ; (2021[34]) The carbon footprint of bitcoin, https://www.dnb.nl/en/publications/publicatieoverzicht/research-publications/analysis/the-carbon-footprint-of-bitcoin/.

Figure 1.2. Energy consumption of Bitcoin mining comparable to entire nations (2021)



Note: The values shown are gross of Bitcoin mining that occurs in the countries, therefore these may be underestimating the actual amount of energy consumption of Bitcoin mining.
Source: https://digiconomist.net/Bitcoin-energy-consumption

1.2.1. The carbon footprint of Bitcoin

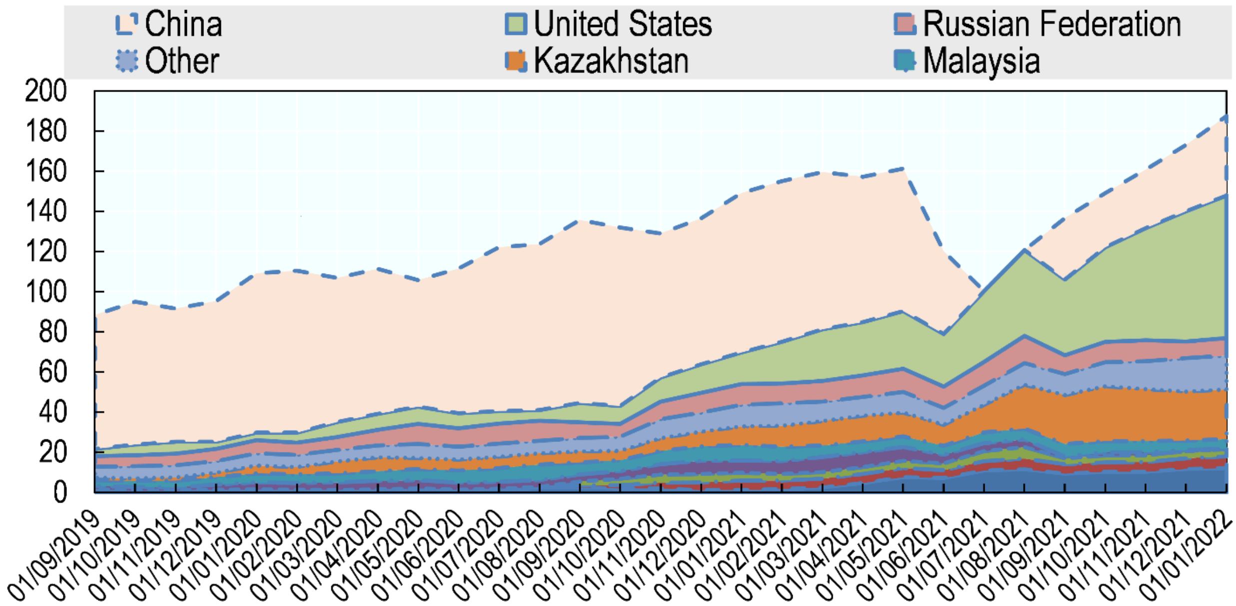
Carbon emissions from the Bitcoin network have been described for some time as comparable with country-level carbon footprints. Empirical findings using IP addresses of miners and average emission factors from the IEA suggest that the Bitcoin network had similar levels of carbon emission as Jordan and Sri Lanka in 2018 (22 to 22.9 Mt CO_2) (Stoll, Klaaßen and Gallersdörfer, 2019[28]).[12] In addition, the equivalent carbon impact without any use of renewables would have resulted in the emission of 51 Mt CO_2. Before the crypto-asset mining ban in China, estimates of energy consumption by Bitcoin and Ethereum mining stood at 43.9 Mt CO_2 emissions per year, which is comparable to the emissions footprint of 6.8 m Europeans (Trespalacios and Dijk, 2021[34]). The results of a 2020 DNB study estimate the carbon footprint of a single Bitcoin transaction to be 402 kg of CO_2, which is two-thirds of the average monthly carbon emissions of a Dutch household (611 kg CO_2). A recent report from the US Office of Science and Technology Policy estimates that global electricity generation for the crypto-assets with the largest market capitalisations resulted in a combined 140 ± 30 Mt CO_2 per year, or about 0.3% of global annual greenhouse gas emissions (White House, 2022[35]).

Rises in Bitcoin prices drive miners' profitability upwards, further incentivising the operation of more energy-intensive mining equipment and possibly increasing the carbon emissions of the network. In 2020, the carbon footprint of the Bitcoin network was estimated to have increased by 25% (reaching 45 Mt) despite a decrease in the number of transactions (down by 6% to 112m) (Trespalacios and Dijk, 2021[34]). Considering that the energy mix remained relatively constant and the number of transactions decreased, such growth was attributed to the growth in the computing power (i.e. hash-rate) of the Bitcoin network

[12] The study acknowledges that the miners can conceal their location, but did not take this into account in the calculations because doing so would hinder Bitcoin mining: less-than-optimal network connection, as a result of using TOR or VPN, would put the miners at a disadvantage.

(which grew 30% in the same period, from 54 to 70 TWh). This growth can be attributed to higher Bitcoin prices in 2020 relative to 2019.

Figure 1.3. Evolution of network hash-rate by country



Source: CCAF (2022[26]), Cambridge Bitcoin Electricity Consumption Index (CBECI), https://ccaf.io/cbeci/mining_map .

Work done by de Vries and Stoll to quantify the e-waste resulting from mining operations illustrates why this is an additional area of environmental concern. As of May 2021, Bitcoin's annual e-waste generation was estimated to be 30.7 metric Kt, comparable in volume to the small IT equipment waste produced by a country such as the Netherlands (de Vries and Stoll, 2021[36]).[13] This is nearly a three-fold increase compared to a 2019 estimate of Bitcoin network's e-waste of 11 metric Kt (de Vries, 2019[37]). In contrast to other general-purpose computing hardware, modern crypto-asset mining infrastructure, such as ASIC, is designed to perform a single task. With the race for more powerful mining tools, the mining hardware quickly becomes obsolete and useless: on average, Bitcoin mining hardware as of 2021 may have a useful life of less than 1.5 years (de Vries and Stoll, 2021[36]).

[13] The same study suggests 234 grammes per Bitcoin transaction on average.

2 Transitioning to less energy-intensive solutions for digital assets

Given the important considerations around the environmental impact of digital assets, efforts are being made to reduce the energy consumption and the carbon footprint associated with crypto-asset mining. This section outlines several of these efforts, include the transition of existing PoW-based crypto-assets to Proof-of-Stake (PoS); the development of consensus mechanisms other than PoW and PoS; the comparison of PoS to conventional finance; and the increasing importance of this debate given the increasing institutionalisation of crypto-assets and Bitcoin holdings by institutional investors in traditional financial markets.

2.1. Alternative consensus mechanisms to PoW

PoS and other alternative consensus mechanisms to PoW do not have the same environmental impact. Most recently, the Ethereum blockchain on which the second largest crypto-asset (Ether or ETH) is based, transitioned to PoS through a process known as 'the Merge'.[14] Other important blockchains utilising the PoS mechanism include Cardano, Solana, Algorand, and Tezos, while others, such as Stellar, use different mechanisms relying on the agreement of trusted nodes. Alternative consensus mechanisms are increasingly gaining ground due to their limited environmental impact when compared to the Bitcoin blockchain, but these still demand greater energy consumption than non-DLT architectures (see Section 2.3.2).

Table 2.1. Illustrative comparison between PoW and PoS

	PoW	PoS
Probability that a particular node will conduct verification of transactions in a block	Computing power	Staked crypto-assets
Computational difficulty	Difficult	Easy
Energy consumption	High	Low
Computing hardware	Single purpose (used for PoW mining)	General purpose
Barrier to entry	Computing hardware	Crypto-asset deposit
Transaction speed	Slow	Faster

[14] On 15 September Ethereum performed a software update, known as the Merge, where it altered its proofing mechanism of transactions from the high energy consuming mechanism of PoW to the less energy consuming Proof-of-Stake (PoS).

	PoW	PoS
Name of the actors who verify transactions	Miners	Validators
Incentive to behave honestly	High computing power needed to manipulate the network	Penalty on staking deposit for dishonest behaviour
Potential shortcomings	51% attack (collusion of powerful mining nodes) Barrier to entry (powerful hardware needed) Lack of scalability Relatively higher energy consumption Electronic waste	51% attack (collusion of large stakeholders) Barrier to entry (large deposit needed) Nothing-at-stake attack (multiple forks) Unexpected flaws could be discovered as popularity of PoS grows
Examples	Bitcoin Ethereum pre-Merge (up to mid-Sept 22) Dogecoin	Ethereum post Merge (as of mid-Sept 2022) Cardano Solana

2.1.1. Transitioning to PoS: the example of the Ethereum blockchain

The Ethereum blockchain upgrade from the original PoW mechanism to PoS, completed in September 2022, was expected by the industry to reduce Ethereum's energy consumption by c.99% (Ethereum.org, 2022[38]) (de Vries, forthcoming). In reality, however, the overall benefit to the environmental impact of crypto-mining may have been lower, as miners are reported by media to have migrated to Bitcoin mining after the Merge, in order to use the capacity they already have for PoW consensus mechanisms. This reportedly resulted in a record computing power dedicated to Bitcoin mining (Bloomberg, 2022[39]).[15] The process consisted of the merging of the original Ethereum main net[16] with a separate PoS blockchain (called the Beacon Chain).[17] Prior to the Merge, a single Ethereum transaction would consume electric power comparable to one week of energy consumption by a typical American household (Castor, 2022[19]). Instead of relying on crypto-asset miners, the PoS validation mechanisms relies on nodes holding network tokens (a stake) and having an interest in maintaining the integrity of the network. In concept, nodes validating transactions have no incentive for double spending or creating fraudulent transactions (51% attacks) because they risk losing their stakes and the right to participate in the network in the future.

One of the main drivers of the Merge was the recognition that the significant power consumption of PoW mining activities, as well as the obsolescence of single purpose mining hardware used for PoW validation, is a limiting factor to scalability. Following the Merge, Ethereum's scalability is expected to be further enhanced through new technological innovations (e.g. rollups and shard chains). These innovations, combined with future expected upgrades of the Ethereum blockchain may allow the number of Ethereum transactions to increase substantially, although it still remains uncertain if these upgrades will be successful. Sharding, the next planned upgrade of the Ethereum network, is expected to allow for further reduction of the environmental impact of the Ethereum blockchain as it may, according to the Ethereum Foundation, reduce hardware requirements associated with validating nodes. In particular, validators may no longer be required to store as much data on their own devices, but instead may be able to use data techniques to confirm that the relevant data has been made available by the network as a whole, thus reducing the cost of storing data (Ethereum.org, 2022[40]).

[15] Non peer-reviewed estimates suggest a real reduction of energy consumption for the overall crypto-asset mining activity to be c.35%, because of the mining power that has been diverted to mining Bitcoin (Rosenthal, 2022[65]).

[16] A main net is a fully-operational blockchain that has been fully deployed and is in production.

[17] It should be noted that, although the Ethereum blockchain was based on PoW validation mechanism until the Merge, Ethereum has an unlimited supply of crypto-assets which differs from the 21 million supply set in the Bitcoin protocol. Ethereum supply increases according to the constant rate of issuance, which can change whenever the community agrees to do so on the updated protocols.

Box 2.1. Other types of blockchain consensus mechanisms with lower environmental impact than PoW

Variations of the PoS mechanism allow their crypto-asset owners to lend the right to validate transactions in exchange for a shared profit. This enables small stakeholders to earn rewards in a PoS network. Bonded Proof of Stake (BPoS) is a protocol, in which owners of its crypto-asset can choose to delegate the validation stakes to another actor without the transfer of the crypto-asset. The token holders can also vote on amending the protocol. Stakes of delegator and validator can be slashed, if the validator, who may or may not be the delegator, does not follow the BPoS protocol.

Proof of Authority (PoA) is a centralised consensus mechanism, in which only a group of validators can validate transactions. Depending on the exact types of PoA, there are different criteria to select a validator, such as arbitrary reason, vote, stake, and reputation. In PoA, rather than staking tokens, those in the network stake their own reputation or authority. The underlying principle suggests that if the nodes prove to be unreliable, they lose their authority and can no longer validate blocks. PoA uses fewer block validators and has proven to be faster than PoW and PoS. It is well-suited to permissioned blockchains, as it does not necessarily need to rely on a reward mechanism (e.g. Microsoft Azure and VeChain).

In Delegated Proof of Stake (DPoS), crypto-asset owners vote on the delegate who validates transactions. A larger stake of crypto-assets in DPoS grants the owner a greater voting weight. Voters and delegates share the validation rewards which incentivises an honest behaviour. Furthermore, voting is a continuous process which means that fraudulent delegates can be quickly replaced. Voting requires a low stake and DPoS protocols keep a fixed number of delegates.

Liquid Proof of Stake (LPoS) shares similarities with BPoS. LPoS crypto-asset owners have the option to delegate validation stake while retaining the crypto-asset. The owners can also amend the protocol. However, owners' crypto-asset is not exposed to slashing when validators exhibit a dishonest behaviour. Instead, only the validator is punished for his or her undesirable behaviour.

In Nominated Proof of Stake (NPoS), anyone who chooses to be a nominator can indicate the validators that he or she trusts. NPoS protocol takes this nomination into account as it selects a limited number of validators who can build reputation over time. Validators can be rewarded for following the protocol, or have their staked tokens slashed otherwise. Nominators share validators' reward, if the protocol selects their nominee to be a validator, and the validator follows the protocol.

Pure Proof of Stake (PPoS) adheres to the essence of a PoS protocol. PPoS often has a low staking requirement to participate as a validator, which enables an ease of participation. In exchange, there is no inherent mechanism to dissuade fraudulent behaviour other than slashing, which takes away a portion of the staked crypto-asset if a validator does not follow the protocol. Higher stake would grant validators with a higher chance to validate the transactions and receive the reward.

Miners under Proof of Burn (PoB) protocol can increase their chance of adding a block by burning their crypto-assets. Miners can burn a crypto-asset by sending it to a designated un-spendable address. Consequently, PoB protocol can reduce inflation, but it does not imply that successful miners will be profitable. In a way, value lost by burning a PoB crypto-asset is comparable to purchasing powerful mining hardware in PoW. Since computing hardware does not affect consensus mechanism, PoB networks spend less energy than PoW networks, and mining pools observed in PoW do not form.

Proof of Capacity (PoC), also known as Proof of Space, relies on computer storage to determine block mining (Vranken, 2017; Andoni et al., 2019; Bashar et al., 2019). Unlike PoW in which computing power determines the likelihood of validating a transaction, miners compete with one another using data stored from the PoC network. Thus, powerful computing hardware provides no benefits in PoC mining.

Although PoC networks consume much less energy than PoW would, PoC has security problems such as nothing at stake in which attackers can create forks at a low cost.

Proof of Elapsed Time (PoET), developed by Intel, is a consensus mechanism on a permissioned network. As a permissioned network, all participants' identity is revealed before accessing this private network. Blocks are generated from the node that has the shortest time to do so, which is randomly decided and resembles a fair lottery system. Thus, PoET protocol does not depend on energy or stake. Perhaps the extreme centralised nature of PoET is repulsive to the crypto-asset community. Only Hyperledger Sawtooth, a digital ledger developed by Linux and Intel, uses PoET as of early 2022.

Proof of Importance (PoI) is a similar consensus mechanism as PoS, but it uses the net transactions in addition to the stake to determine who can validate the transactions (Beikverdi, 2015; Bashar et al., 2019). An advantage of this system is that it resolves the issue of PoS that rewards wealthy crypto-asset owners. Instead, taking account of net transactions rewards important PoI users who actively partakes in using their PoI crypto-assets. These active users should be considered as important in the PoI network because they contribute to the continuation of the blockchain. Net transfer, rather than total, is used because a fraudulent user can transfer the PoI crypto-assets to oneself to manipulate the system. Recent transactions are considered to be more important than the old transactions.

Overall, a distinction should be made between public and permissioned blockchains, as the latter will typically consume less energy for every chosen consensus mechanism.

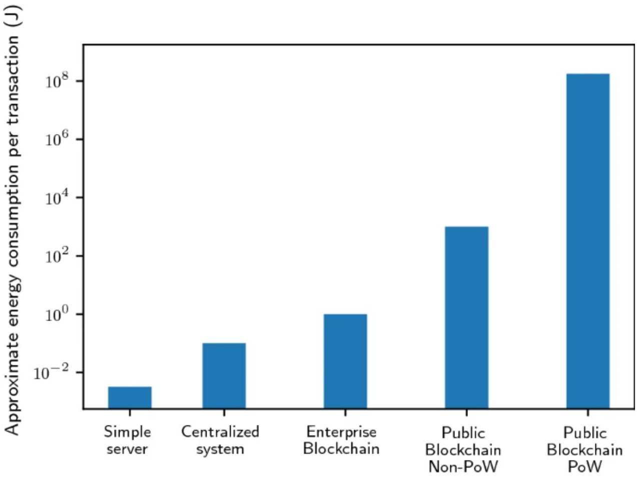
Source: Andoni et al. (2019[41]), Blockchain technology in the energy sector: A systematic review of challenges and opportunities, https://doi.org/10.1016/j.rser.2018.10.014; Frankenfield (2022[42]), Mining Pool: Definition, How It Works, Methods, and Benefits, https://www.investopedia.com/terms/m/mining-pool.asp.

2.1.2. PoS vs. traditional finance

Although there is general agreement that PoS consumes several orders of magnitude less energy than PoW networks, the comparison of PoS with traditional finance is inconclusive at this stage. The uncertainty is in part due to the different and difficult to calibrate assumptions used in academic studies. Most studies tend to agree that while PoS is an improvement from PoW in terms of energy consumption in relative terms, it should not be considered to be a solution to the environmental impact of digital assets in absolute terms. Also, a direct comparison between PoS blockchains, which are an infrastructure technology, and the energy consumption of financial sector activity may not be an appropriate comparison.

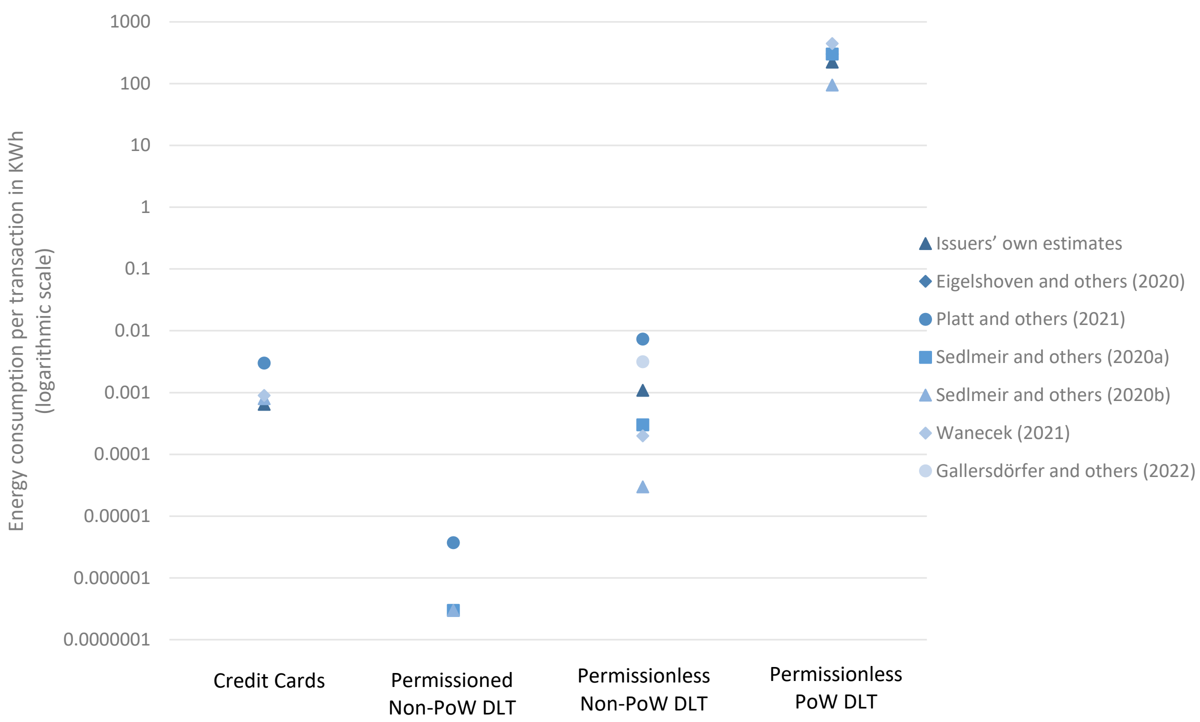
A recent compilation of estimates by IMF staff shows that non-PoW protocols can consume a similar amount of energy per transaction as credit cards (IMF, 2022[43]). The study focuses on the energy consumption involved in the processing and settlement of payments, that is, credit card companies' data centres and DLT consensus mechanisms. Additionally, the study suggests that non-PoW permissioned networks have the potential to consume less energy than credit cards. This potential does not necessarily emanate from the nature of DLT systems as compared to traditional centralized systems, but can be driven by legacy systems used by credit card processors, which raise their energy consumption. Even though innovation and returns to scale can alter the energy consumption of the different technologies, it is unlikely to alter the ranking of the different crypto asset categories in terms of energy efficiency.

Figure 2.1. Comparison of energy consumption per transaction for different crypto-asset and non-blockchain architectures



Source: Sedlmeir et al. (2020[44]), The Energy Consumption of Blockchain Technology: Beyond Myth, https://doi.org/10.1007/s12599-020-00656-x.

Figure 2.2. Estimates of energy use (in kWh) per transaction for the core processing of different payment systems



Source: IMF (2022[43]) Digital Currencies and Energy Consumption, https://www.imf.org/en/Publications/fintech-notes/Issues/2022/06/07/Digital-Currencies-and-Energy-Consumption-517866 .

2.1.3. Why is PoW still a concern? The importance of Bitcoin as the "mainstream" crypto-asset that institutional investors prefer

Despite the recent transition of the Ethereum from PoW to PoS, PoW still dominates the consensus mechanisms used by crypto-assets given the weight of the Bitcoin in the overall crypto-asset market. For the Bitcoin blockchain to move to PoS, the majority of the network would have to agree and adopt the change, and the blockchain would get updated through a "fork". If there exists no common agreement within the network, the blockchain might still be updated, but it will probably be split into different versions running in parallel: one implementing the changes and the other continuing without the update (assuming enough participants continue to participate in the older version).

It is unlikely that a similar transition from PoW to PoS could occur for the Bitcoin blockchain, given that the Bitcoin appears to be a highly decentralised network with an absence of a centralised authority to drive such a decision by the network. Additionally, a perception by parts of the crypto-asset community about PoW guaranteeing stronger security for the network,[18] the incentives of some Bitcoin holders related to mining (e.g. sunk cost investments in mining equipment and switching costs), and a community that has been historically unwilling to deviate from the original protocol,[19] are all obstacles to a transition to a PoS validation mechanism.

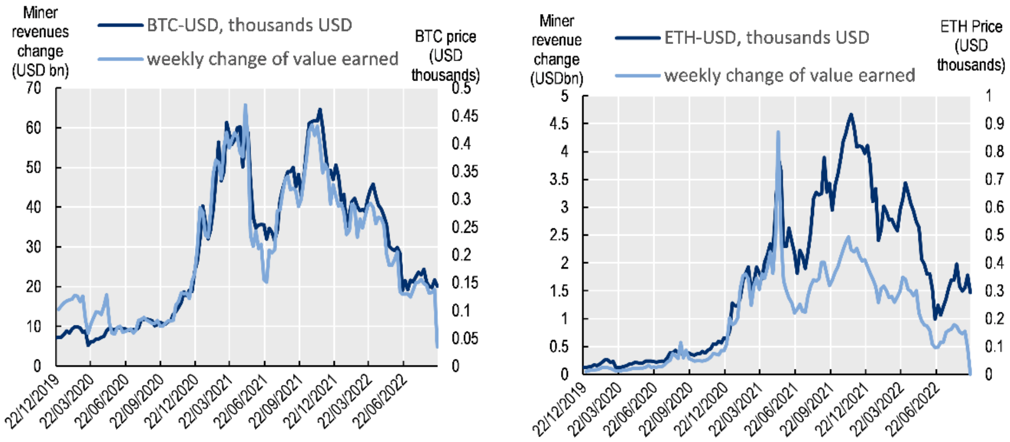
Bitcoin is the main crypto-asset among professional and institutional investors participating in crypto-asset markets (OECD, 2022[9]), and the environmental impact of its consensus mechanism gives rise to climate transition risks for such investors. Bitcoin's high energy demands may be incompatible with ESG objectives of financial market participants and their shift towards a low carbon transition. This tension would be expected to increase as crypto-asset markets and traditional financial markets become more interconnected (OECD, 2022[9]). What is more, the intensity of crypto-asset mining activity (and the associated environmental impact) is linked to the price of the Bitcoin and Ether as miners' or validators' rewards comprise newly minted assets and transaction fees (see Figure 2.3). The greater the value of the index, the greater the historical incentive that miners or asset issuers have had to generate the asset.

[18] It is generally accepted that PoW provides a high level of security at the cost of energy efficiency and speed.

[19] There has been a movement to increase the Bitcoin block size to enable Bitcoin transactions to scale up, but much of the original Bitcoin community did not wish to deviate away from the original protocol. Consequently, the Bitcoin community retained Bitcoin at its original form even if it limited the scalability that is necessary to use Bitcoin as a digital currency, which is what the founder of Bitcoin Satoshi Nakamoto envisioned Bitcoin to be.

Figure 2.3. Miner rewards and crypto-asset price evolution

Bitcoin (LHS) and Ether (RHS)



Note: The figures depict the cumulative and weekly change of the total USD value of newly mined or issued assets plus fees (in USD billion) over the past 1 000 days. It reflects the value earned by those generating the crypto-asset.
Source: OECD based on data from Chainalysis.

2.2. A case for the use of renewable energy sources for crypto-asset mining

Energy consumption resulting from crypto-asset mining does not equate to its carbon footprint, as the latter is a function of the energy mix of the energy used. The use of renewables has been advocated as one of the ways to reduce the environmental footprint from mining of crypto-assets. An industry-led survey of 44 mining companies representing half of the global Bitcoin network suggests that the Bitcoin's carbon footprint decreased by 25% year-over-year, as miners moved towards renewable energy sources (58% of energy consumed in that sample came from renewables) (Bitcoin mining council, 2022[45]). But peer-reviewed academic research shows a contrasting result, suggesting that the share of renewables decreased while the carbon footprint increased since the Chinese mining ban in 2021 (de Vries et al., 2022[1]).

Even if renewable energy can reduce the carbon footprint of mining, such energy may be better utilised by other sectors that are more beneficial to the economy. The use of temporary excess renewable energy generation is not a credible alternative either, as these may be hard to combine with the 24/7 nature of Bitcoin mining.

The current lack of cost-effective renewable energy storage, given that such energy resources are subject to seasonality and weather conditions, further aggravates concerns about powering crypto-asset mining with renewable energy. China during 2020 presents a good case study of this issue. Crypto-asset miners relied on cheap hydro-electric power in Sichuan during the wet months, but crypto-asset mining activities took place in other provinces such as Xinjiang and Inner Mongolia, which have cheap coal-fired energy during the dry months (Trespalacios and Dijk, 2021[34]). As such, a higher proportion of renewable energy in crypto-asset mining can reduce the carbon footprint at certain times of the year, but this may not be a reliable solution.

As with the energy consumption levels, there is uncertainty about the data for the share of renewable energy used in Bitcoin mining. Limited transparency of reported data of crypto-asset mining activities, self-reporting of such estimations with disclaimers or without third party validation and the high competition within this industry cast doubt over the credibility of industry data. Academic estimates about the share of renewables range from 29% to 73% over the period of less than a year (Carter, 2021[22]).

In emerging economies, there are questions about the ability of energy grids to support crypto-asset mining due to reliability issues. There may also be a reduced ability to monitor the sources of energy used to ascertain its cleanliness.

2.3. Grid 'load balancing'

Some proponents of crypto-asset mining assert that energy-intensive mining activity can improve the resilience of energy grid infrastructure by facilitating 'load balancing'. In periods of high demand for grid electricity, during which marginal electricity consumption may also become expensive, crypto-asset miners can quickly turn off part or all of their operations. The ability of crypto-asset miners to modulate energy demand could in some circumstances avoid or mitigate spikes in electricity consumption (load). In extreme cases, this function can help avoid blackouts, and it can be operationally and economically beneficial to grid operators. In some jurisdictions, crypto-asset miners can be paid for the "service" they provide to the electricity grid by quickly curtailing their energy use (Utilitydive, 2022[46]).

However, crypto-asset miners contribute to overall increased energy demand, which all else equal makes it more likely that demand spikes will exceed grid capacity. In such circumstances, load balancing becomes more valuable. Therefore, where grid operators may pay crypto-asset miners for load balancing, the operators and miners have misaligned incentives (White House, 2022[35]). More generally, because crypto-asset miners have incentives to run their equipment continuously, they will likely only curtail demand if the benefits to doing so (or penalties for failing to do so) exceed the value of the marginal minted crypto asset. Load balancing therefore becomes less likely as crypto-asset values increase, and in many jurisdictions, coal and natural gas generation is used to meet spikes in demand.

2.4. Approaches to the environmental impact of DeFi, CBDCs and tokenisation

Since the Ethereum Merge, DeFi is less reliant on energy-intensive practices such as PoW. The majority of DeFi protocols were built on Ethereum, because of its smart contracts functionalities (OECD, 2022[47]). Other PoS-based blockchains are increasingly being used for the development of DeFi apps. What is more, DeFi protocols are usually Layer 2 and Layer 3 solutions[20] built on top of the underlying blockchain, without generating additional energy demand.[21]

At the moment, most CBDC projects are based on non-PoW permissioned blockchains or on upgraded versions of traditional payment architectures (e.g. RGTS). For example, the Banque de France's pilot is built on Tezos, and the Marshall Islands' Sovereign currency is built on Algorand, both designed for PoS. Private permissioned DLT systems such as Hyperledger Fabric are also used, for example in the pilot by Eastern Caribbean Central Bank or the operational CBDCs in Bahamas and Nigeria.

CBDC design objectives are focused on speed, cost, scalability, and efficiency. At the same time, the use of DLT is not mandatory in the development of CBDCs, in which case the entire question of consensus mechanism is obviated.

PoW would not be beneficial for the development of CBDCs: the decentralised security model of PoW with its public, permissionless focus would not fit with the likely needs of a CBDC. Rather, in such cases forms

[20] Applications that are built on top of an existing blockchain system (Layer 1 or settlement layer).

[21] It should be noted, however, that Layer 2 and 3 solutions may facilitate greater adoption, thus indirectly increasing the overall carbon footprint of the underlying network.

of DLT that provide greater degrees of control and oversight – such as private permissioned approaches, which may also offer programmability and smart contract functionality – are likely better aligned with the expected design objectives.

Regarding the tokenisation of assets such as financial instruments, this can be achieved with any blockchain consensus mechanism. As such, the environmental impact has no relation to the tokenisation as such but rather to the blockchain used to implement the tokenisation. Currently, some industry participants suggest that the reason the Ethereum blockchain is a commonly used platform for tokenisation is because of its first mover advantage, smart-contract capabilities, and the relatively larger developer community, rather than for its environmental impact.

2.5. Beneficial use of DLTs to promote sustainable finance and climate transition

The use of DLTs for data collection, sharing and reporting in financial markets and in particular in the sustainable finance sector, could have the potential to help improve the channelling of financial resources to environmentally sustainable businesses in a more efficient way. While the discussion about the environmental impact of certain DLTs is ongoing, blockchains are being increasingly deployed in Green FinTech use-cases to help promote sustainable finance and assist financial market participants with ESG reporting compliance, as discussed in examples below. Nevertheless, the use of such innovation comes with emerging risks that need to be carefully assessed and mitigated for the safe implementation of such solutions.

Market participants using ESG-related strategies often lack the necessary tools (e.g. consistent data, comparable metrics, and transparent methodologies) to inform their decision-making in an appropriate manner (OECD, 2020[48]). DLTs could possibly play a role in recording and disseminating granular ESG data, leveraging the potentially transparent and auditable nature of blockchains. DLT-based recording and sharing of ESG data could help better inform investment decision-making in sustainable finance from the investor standpoint, possibly addressing part of the data availability challenges of ESG investing. In particular, such technology could allow the storage and distribution of large amounts of data related to companies' sustainability practices that may not be readily available or processed at high speed and in an efficient manner. This, in turn, could allow for more cost-effective screening of ESG investments and could enable real-time verification of reported data-points. It should be noted, however, that DLTs do not resolve the issue of data quality (the so-called 'garbage in, garbage out' problem), as DLTs have no ability to verify the trustworthiness of data imported on-chain.

The immutability and irrevocability of blockchains, if designed to have those features, could potentially contribute to addressing concerns over greenwashing when it comes to supply chains, for example, by enabling a single record of auditable, verifiable and traceable data collected across a company's supply chain. The possible benefits of DLT in this case are underpinned by the tamper-proof, real-time tracking of data provided by multiple stakeholders involved in supply chains across multiple jurisdictions. Examples of data involved include provenance data, greenhouse gas emissions and other impact tracking, as well as compliance with regulatory requirements across the chain. DLTs may be able to deliver more transparency and increased accuracy of supply chain due diligence information, facilitating responsible supply chains, by providing a near-real time overview on all transactions occurring throughout the supply chain, thus allowing for better control in localising risk hot spots and performing risk mitigation (OECD, 2019[49]).

The use of DLTs for tokenised forms of sustainable finance capital market products can potentially provide benefits that go beyond the level of financial market infrastructure and involve sustainable data transparency and credibility. The BIS Innovation Hub, in co-operation with the Hong Kong Monetary Authority, successfully concluded Project Genesis, which consisted of prototype digital platforms for tokenised green bond issuance (BIS and HKMA, 2021[50]). The use of DLTs, among other innovations, allowed for increased transparency, making it easier for investors to track the projects' positive environmental impact in real time through an application.

The use of DLTs for data reporting could also contribute to efforts for efficient and auditable reporting of financial and non-financial ESG data to the market and to supervisory authorities in associated RegTech applications. Conceptual frameworks by academia suggest that DLTs may facilitate the automation of key compliance processes whereby regulators can access compliance data in near real-time and at the international level (Axelsen, Rude and Ross, 2022[51]). Greater potential emphasis on sustainability reporting requirements in many jurisdictions (e.g. EU, Japan) is likely to increase the importance of innovative solutions by firms seeking to lower their compliance costs with streamlined, efficient and effective sustainability data reporting.

Nevertheless, numerous challenges remain to be resolved in the use of DLTs for sustainable finance and ESG investing use cases. In particular, the quality and accuracy of data introduced into the blockchain is not guaranteed and exposes users of such data networks to risks of "garbage in, garbage out", applicable to all data sharing platforms irrespective of technology used (OECD, 2021[52]). The inherent transparency of DLTs is worthless if the data 'on-boarded' on-chain are incorrect, inaccurate or even fraudulent. The bridging of the off-chain to the on-chain world in an accurate and trusted manner is an issue also in the case of tokenised sustainability-linked financial products or green bonds (OECD, 2020[53]). Such risk could be partly mitigated by automated reporting to the blockchain with the use of other innovations such as the Internet of Things (IoT), or through the use of independent third party verifying authorities (OECD, 2021[54]). The issue of interoperability of data is also an important impediment to the wider use of DLTs for reporting purposes, as it could lead to fragmentation of reported data that reduces their comparability and usability, particularly by investors wishing to benchmark or compare ESG performance. When it comes to reporting and RegTech use cases, the emergence of DLT-based RegTech applications triggers an increase in the need for staff with technical knowledge and an investment in skills for the supervisory community.

3 Preliminary policy considerations

The digital assets industry is becoming increasingly important for the financial markets, and the negative externalities of some underlying DLTs on which mainstream crypto-assets are built – in particular Bitcoin – may call for policy intervention. This section discusses the history of policy action until now and offers preliminary policy recommendations to address the environmental impact of digital assets.

3.1. Banning crypto-asset mining at the country level may not be an effective solution

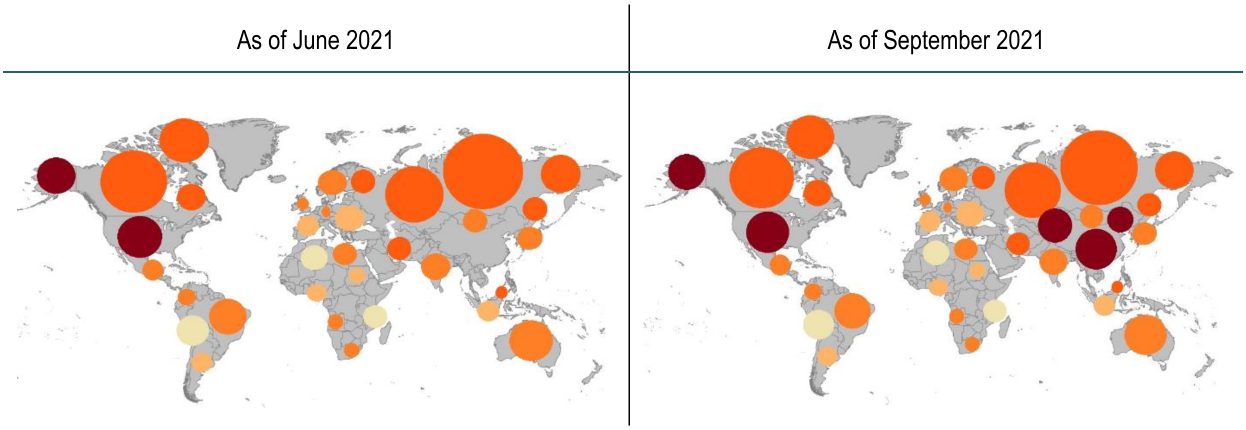
Outright banning crypto-asset mining activity may not be the most effective solution to address the environmental impact of crypto-assets, as it risks displacing or concealing mining activity instead of reducing it. Digital assets are global by nature, and banning it in one region may incentivise the relocation of miners to move to another geography with perhaps a worse energy mix and greater detrimental environmental impact. Bans may also push miners into masking their real locations in order to avoid being identified as operating in a country where restrictions apply (e.g. through IP VPN tools).

The case of the China is a great example of the limits of banning as a policy intervention mechanism. Empirical evidence suggests that the carbon intensity of Bitcoin mining increased as a result of the ban in China, increasing Bitcoin's carbon footprint (de Vries et al., 2022[1]). This was partly attributed to the fact that the share of renewables used to support the Bitcoin network decreased from 41.6% in 2020 to 25.1% following the ban, as the hydroelectric power used in China was replaced by fossil fuels for mining elsewhere. Indeed, instead of ceasing mining activity, the ban pushed miners to relocate and/or continue to operate undercover while hiding their location through technical solutions (CCAF, 2022[55]).[22] As a result, Chinese ban of crypto-asset mining may have had an adverse effect on a global scale.

The supposed exodus of miners from China following the June 2021 ban emphasises the importance of renewables in reducing the carbon footprint of crypto-asset mining. Following the China ban, mining activities may have relocated to other parts of the world offering cheap electricity and favourable regulation. In aggregate, about USD 6bn worth of mining activities moved to countries such as Kazakhstan, Russia, and the United States. Kazakhstan has been receptive to crypto-asset mining given the possibility to use cheap energy from fossil fuels to generate an expected USD 1.5 bn in government revenue over five years (McGregor, 2021a). However, parts of Kazakhstan have experienced electricity shortage since July 2021 and were obliged to import energy from Russia during the winter (Fortune, 2021[56]).

[22] The fact that miners can hide their locations further limits the accuracy of any estimates of location-based power use and carbon intensity.

Figure 3.1. Migration of Bitcoin mining suggests bans are inefficient to curb global impact



Source: Based on the World Bitcoin mining map, Cambridge Centre for Alternative Finance.

3.2. There is still a need to address the environmental impacts of crypto-asset mining

Although an outright ban may not resolve the issue of crypto-asset mining at the global level, restrictions could be applied to the energy sources used for such activity to mitigate the negative impacts created (Gola and Sedlmeir, 2022[57]). For example, outright restrictions around the use of fossil fuel for crypto-asset mining activity could be a way forward. This could be possibly enacted in combination with guidance about or restrictions on the energy mix and the use of renewables for any such activity.

Given that specific consensus mechanisms (PoW) are the major source of negative impacts in this space, rather than implementation of sweeping actions at an industry level, there may be merit in focused policy action on this specific consensus mechanism. This may also avoid policy actions that stifle innovation in the financial sector and beyond. DLTs are not a homogenous product, and different approaches may be needed to meet different infrastructure demands. Also, the potential benefits of DLTs go beyond digital assets, and as such, the discussion could be nuanced and broadened to include other use-cases of this infrastructure technology.

3.3. Addressing the data gap and disclosure

One of the largest impediments to any assessment of the need for policy action is the lack of high quality, consistent data about the environmental impacts of such activity. As considered in this report, there is a large divergence in data estimates depending on the methodologies and assumptions used, and it can therefore be difficult for policy makers to perform accurate analysis and determine how to best approach this space.

In order to close this data gap, policy makers could consider requiring disclosure of the energy consumption of crypto-asset miners and validators, in line with other sustainability-related disclosures. This approach has its limitations, given that some of this activity may be anonymous/ pseudonymous or disguised (e.g. IP tools). Independent assessments of the estimated carbon footprint could also be considered to ensure the robustness of such assessments. In addition to disclosure requirements, fostering best practices and incentivising the industry to agree on common reporting standards or benchmarks could be a first step towards greater transparency. The existence of qualitatively sound data is essential for any informed discussion around the environmental impact of DLTs, including – but not restricted to – crypto-asset mining.

3.4. Institutionalisation of crypto-asset mining and climate transition risks for institutions participating in markets for crypto-assets

The carbon footprint of the Bitcoin may also undermine the climate transition paths of those traditional financial market participants who have been increasingly investing in Bitcoin in recent years. Increased participation of institutional investors in digital asset markets and the growing institutionalisation of crypto-assets gives rise to significant investor risks at the micro-level and to potential systemic risks at the macro level (OECD, 2022[9]). In addition to already identified risks, investors may also be undermining their ESG strategies or climate transition paths, given that most of the environmental impact stems from the Bitcoin blockchain, where the majority of institutional investors in crypto-asset markets are active.

It is therefore important that investors have the data and tools necessary to apply sustainable finance alignment tools to their digital asset investments. For example, the appropriate classification of different DLT-based activity, and PoW mining in particular, in taxonomies of sustainable activities, may be a way forward where these exist. Investors may also use other principles-base alignment tools to understand the impact of Bitcoin holdings on the sustainability of their portfolios.

3.5. The need for international co-operation and co-ordination

Given the inherently global nature of such assets and markets, some level of co-ordination needs to be encouraged at the cross-border level. As evidenced in the case of crypto-asset mining bans, in the absence of international co-ordination, the negative impacts are being transferred from one geography to another, but the overall impact to the environment remains. It is therefore important to achieve some level of agreement about the policy action to limit negative environmental impacts at the cross-border level.

3.6. Support for the development of beneficial use-cases of DLTs for sustainable finance

In line with the OECD Recommendation on Blockchain and other DLTs, the sustainable use of Blockchain should be supported, while identifying and mitigating any negative environmental impacts (OECD, 2022[58]). DLTs have to potential to act as tools to improve transparency, create accountability, and potentially reduce negative externalities in various sectors, and could be harnessed for the promotion of sustainable finance. The use of DLTs for data collection, sharing and reporting, and the issuance of tokenised green financial instruments are just some of the examples of applications that can help improve the channelling of financial resources to environmentally sustainable businesses in a more efficient way. At the same time, the use of DLTs for such purposes entails a number of important risks that need to be identified and addressed, associated with data governance, data quality, operational risks, investor and market risk, and other emerging challenges.

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