The impact of the Eurosystem's monetary policy on Bitcoin and other crypto tokens

Bitcoin and other crypto tokens attract significant attention, mainly due to their considerable fluctuations in value and, in some instances, high market valuations over a multi-year comparison. There is much evidence to show that monetary policy has a key impact on a number of conventional assets, and it could therefore be assumed that this also holds true for the prices of crypto tokens. For example, it is sometimes claimed that accommodative monetary policy may have contributed to the value gains seen by crypto tokens. This article explores the influence of monetary policy – particularly that of the Eurosystem – on the prices of Bitcoin and other crypto tokens.

Initial indications that the Eurosystem's monetary policy may have an effect on the prices of crypto tokens are found when narrow time windows around monetary policy announcements are analysed. For example, crypto tokens' considerable volatility and otherwise virtually non-existent correlation with other assets tend to be greater at times when monetary policy news is communicated. At the same time, however, there is also evidence to suggest that monetary policy has greater significance for the responses of share prices and exchange rates, for example, than for the responses of crypto token prices.

This impression is confirmed by an econometric analysis using vector autoregressive (VAR) models that can take account of the interdependencies between monetary policy and financial market developments. These models can be used to isolate monetary policy impulses and depict their effects on asset prices over a longer period of time. It is evident here, too, that the Eurosystem's monetary policy has a significant impact on the prices of major crypto tokens, but that these impulses explain only a small fraction of the volatile price developments.

There are a multitude of ways in which crypto tokens differ in design from conventional assets. For instance, these tokens are units of account in distributed payment systems that are transferred using cryptographic procedures. Since amounts of value can be transferred digitally in a largely anonymous manner, tokens are also used for illegal purposes. There are often no central issuers, and new tokens are created on the basis of defined rules that do not allow for any flexible adjustment of the number of tokens in circulation, such as in response to changes in demand. These particular features are also reflected empirically in that they contribute to the prices of crypto tokens fluctuating more strongly than share prices or exchange rates, for example, with which token prices have hardly any correlation. Thus, crypto tokens primarily serve as speculative assets; however, they are hardly suitable as a means of payment or a store of value, let alone as a unit of account.

Introduction

Growing interest in Bitcoin and other crypto tokens

Bitcoin and other crypto tokens[1] have been attracting increasing attention from the general public as well as among financial market participants for some time. Originally conceived as a digital means of payment without the involvement of intermediaries, they remained little more than a niche phenomenon for many years. However, they are increasingly being met with the interest of a wider range of private and institutional investors. This interest is attributable, amongst other things, to the pronounced fluctuations in the value of crypto tokens compared with other assets as well as their valuation level, which, in the case of some tokens, has increased on multiple occasions in the past. However, in this context, it is also often claimed that prices are driven by speculative excess, as Bitcoin and other crypto tokens have no inherent value and are not backed by underlying collateral[2] for which they could potentially be exchanged. Another view that is sometimes expressed is that accommodative monetary policy has contributed to the value gains of crypto tokens.

Central banks are interested in the impact of monetary policy on asset prices …

Central banks fundamentally have great interest in the impact of monetary policy on asset valuations. For example, changes in asset prices can provide an indication of the effectiveness of various monetary policy transmission channels. At the same time, crypto tokens such as Bitcoin are often purchased in the hope that they avoid the risks associated with conventional monetary policy. For instance, Bitcoin was designed to be limited in supply and is therefore automatically scarce in order to preserve its value over the long term.

… as well as on crypto tokens

The impact of the Eurosystem's monetary policy on Bitcoin and other crypto tokens is analysed systematically in this article. This may help us gain a better understanding not only of the role crypto tokens play in the financial system, but also of the origins of their large fluctuations in value.

Differences between crypto tokens and conventional assets

Bitcoin conceived in the wake of the financial crisis …

The oldest crypto token, Bitcoin, was created in 2008 with the aim of laying the foundation for a decentralised and largely anonymous electronic payment system.[3] Additionally, in view of the experience gained from the escalating global financial crisis at that time, the system was intended to be independent from commercial and central banks, which play key roles in the traditional financial and payments system.[4] This is because banks act as intermediaries – they carry out electronic payments by transferring funds from one account to another. Furthermore, the stability of the value of the currency itself is determined by the actions of commercial and central banks: if commercial banks become distressed, holders may lose confidence in the value of the money created by these institutions. The massive interventions made by central banks in the wake of the financial crisis also caused some observers to have concerns about the risk of inflation that could erode the value of the euro.[5]

… as a decentralised means of payment …

These considerations influenced the design of Bitcoin (see the box on pp. 63 ff.) in two ways: first, payments should be settled in a decentralised manner. Whilst only the system operator, such as a bank, can execute and view payments in the case of central database systems, Bitcoin transfers are validated by many different

1 A crypto token is a digital token that is transferred within a network using a technical protocol based on cryptographic procedures.
2 There is a specific category of crypto tokens – known as stablecoins – that is designed so that its price is stabilised vis-à-vis a reference value. The circulation of stablecoins is often backed by conventional assets; see the box on pp. 68-70. This specific form of token is not the focus of this in this article, however.
3 See Nakamoto (2008). Information on crypto tokens and the underlying technology in payments and securities settlement can be found in Deutsche Bundesbank (2017b) and Deutsche Bundesbank (2019).
4 See Nakamoto (2009).
5 Deflation – i.e. an increase in the value of the euro vis-à-vis goods – is also detrimental to the function of money as a means of payment. Many central banks therefore base their monetary policy around keeping the value of their currency stable against goods and services.

How Bitcoin works

Bitcoin, at its core, consists of a database of transactions referred to as a ledger, which is extended with each entry according to a rigid set of rules. In contrast to centralised databases – such as the account systems of commercial banks – the Bitcoin ledger is publicly viewable, maintained in a decentralised manner by many different network participants and distributed across a computer network.[1] This distributed ledger is updated when new transactions are carried out. The payment units are called bitcoins.[2] In order for a decentralised payment system to function, it must first solve two fundamental problems: it must not be possible to carry out transactions without authorisation – that is, without the payer's permission – and it must be possible to keep the ledger both synchronised across the whole network and immune to alterations to completed transactions. Bitcoin solves these problems using cryptographic mechanisms.

If the ledger is distributed and designed to operate without a central authority, how, then, can individual participants be prevented from creating unauthorised entries? In other words, what is to stop system participants from simply writing an arbitrary number of transactions in the ledger with themselves as the payee, entirely without the consent of the payer? The answer lies in digital signatures. In a conventional centralised payment system, only the payer, the payee and the central authority, such as a bank, have knowledge of the transaction. The bank can use identity checks – such as checking a signature or a PIN – to determine whether a transaction is actually being carried out by the person whose account is being debited. In Bitcoin's decentralised, public payment system, participants are assigned public keys – comparable to account numbers – in the form of character strings, between which transactions are carried out. Payments can be digitally signed by the sender via the additional use of a private key – roughly equivalent to a PIN or password.[3] A digital signature can only actually originate from the payer if the private key they enter corresponds to their public key, which any participant in the system can easily verify using cryptographic algorithms without needing to know the private key. As the digital signature, which likewise consists of a simple string of characters, can be copied an arbitrary number of times, payments could, in principle, be duplicated multiple times by any participant in the system as soon as a private key had been entered. This is, however, stymied by the fact that the digital signature is determined not only by the relevant public keys and the payment amount, but also by a unique identification number. If the same digital signature were copied and used for a second, otherwise identical payment, the second payment would be recognised as invalid and not entered into the public ledger.

If the ledger is distributed across a number of computers, how is it kept synchronised? In other words, how can it be ensured that the same transactions are always entered in the same order on every computer? When a transaction is carried out, its execution must be recorded at every node in the network before further transactions can be carried

1 Methods that rely on these and similar approaches are thus also referred to as distributed ledger technology (DLT). See, for example, Deutsche Bundesbank (2017b).
2 Every bitcoin is made up of 100 million satoshis, named in reference to the author(s) of the Bitcoin white paper, the exact authorship of which is unclear.
3 An introduction to the basics of private-public key cryptography can be found in, amongst others, Auer and Böhme (2020).

out. In fact, the "balance" on each "account" – that is, each public key – implicitly represents the balance of all previous transactions. In order for bitcoins to be transferred at all, therefore, there must have been more recorded inflows than outflows in the past. Payees can only be certain that a transfer occurred if synchronisation is guaranteed. After all, a payee can only truly be sure they received payment if the network participants agree that the amount received was not already transferred elsewhere before the transaction and that this assessment is very unlikely to change. It is therefore of the utmost importance that there is network-wide consensus about the order of transactions. It is in its solution to this problem that the truly innovative aspect of Bitcoin comes to light. Nakamoto (2008) proposed a consensus protocol: a set of rules that, using cryptographic methods, could determine the order of transactions and the right to enter new transactions into the ledger without recourse to a central authority.

The basic principles of the Bitcoin protocol are that entering new transactions into the ledger must entail costs, and that new transactions must build on previous ones. This is achieved by using hash functions. Applying a hash function to any given character string (input) produces a new character string with a fixed number of characters (output), which appears random but is in reality deterministically generated. The vital element in all this is that it is impossible to use the output to discover the input. Thus, if one wished to create an output which fulfilled certain criteria specified by the set of rules – such as an output beginning with a certain number of zeros – there would be no other option than to try a variety of random inputs.

This is how new payments are entered into the Bitcoin ledger: in order for a new payment to be recognised by the network, the participant wishing to enter the payment must have found a valid hash input. As the chances of finding such an input in any one attempt are very low, it can be assumed that an extremely high number of attempts must have been made, which would in turn require the investment of a large amount of processing power.[4] Once the input has been found, however, every participant can immediately use the hash function to verify that it solves the cryptographic puzzle – that is, that it creates an output that meets the requirements. All participants can then update their copy of the ledger to enter the new transactions. Subsequently, the hunt begins anew for inputs in order to add further entries to the ledger. One crucial detail is that the input for the hash function is not entirely random, but instead consists in part of the solution to the previous entry. This ensures that entries in the ledger build on each other, and thus have a set order. This also prevents work being done ahead of time – as the search for a solution always builds on the most recent entry, the search has to be started from scratch if another entry is added to the ledger first.[5]

Why, however, is it necessary in the first place for entering transactions in the ledger to entail costs in the form of the processing power used to solve cryptographic puzzles? The reason can be found in one of the rules of the protocol: that the network should always accept the version of the ledger that

4 As presenting a solution counts as proof of the investment of processing power, this is also referred to as proof of work (PoW).
5 Eyal and Sirer (2014) formally examine the conditions under which it is more valuable to keep a found solution to a cryptographic puzzle to oneself, and instead "secretly" start work on the next puzzle.

contains the most entries.[6] To understand why, it is helpful to imagine an attempt to manipulate the ledger by retroactively changing the chain of transactions in order to, for example, undo certain transactions and spend bitcoins twice (known as double spending). If a participant wanted to attempt this, they would need to present the network with a solution to the relevant cryptographic puzzle for the changed entry, i.e. expend processing power. That would not be all, however: the older the transaction is, the more likely it is that there are already other entries in the ledger which have been built cryptographically on the transaction marked for deletion. When would the network as a whole ignore these entries and instead accept the altered ledger? Due to the rule that new entries must build on the version of the ledger with the most entries, the above would only happen if solutions to cryptographic puzzles for more entries could be presented than had subsequently been found by all other participants. This is extremely unlikely, provided more than half the processing power of the entire network cannot be combined – a feat that would come with high costs attached.[7] The Bitcoin protocol hinges, therefore, upon the idea that the cost of altering payment entries already accepted by the network is prohibitively high, thus protecting the transaction history in the ledger from manipulation.

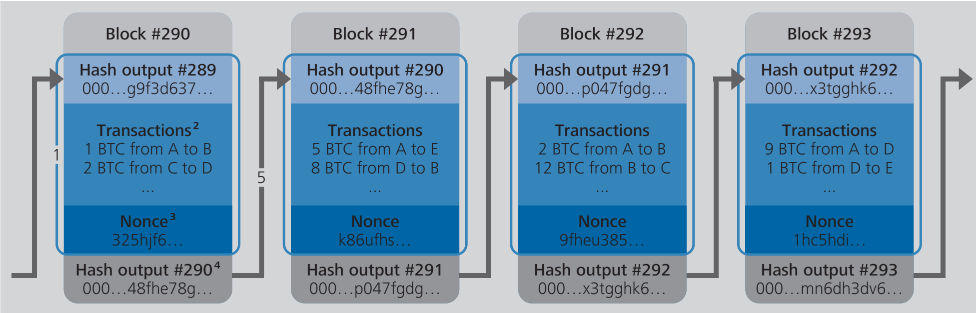
In practice, participants in the network who wish to have their transactions entered in the ledger do not solve the cryptographic puzzles described above themselves. Instead, they leave this job to parties known as miners, who have access to specialised hardware and thus a great deal of processing power. Furthermore, transactions are not entered into the ledger individually, but are instead combined by miners into blocks ahead of time. As the ledger is thus entirely made up of a chain of blocks that are strung together, it is also referred to as a blockchain, which is extended entry by entry.[8] The chart on p. 66 shows an example of the result of the process described above.

Adding new blocks entails high costs for miners, not only due to the high-performance hardware required but above all due to the enormous energy consumption involved.[9] They are reimbursed for this in two ways. First, participants can add fees to their transactions. In particular, when transactions need to be marked as higher priority and many participants want to make payments at the same time, they increase these fees. They do so in order to be selected as quickly as possible by miners, who bundle pending payments one after another into blocks, which are limited in size. Second, the Bitcoin protocol stipulates that successful miners be rewarded with newly created bitcoins for each new block they add to the ledger.[10]

---

6 This is known as the longest chain rule. For an analysis of its actual suitability for maintaining consensus among system participants, see Halaburda et al. (2020).
7 For an analysis of the probability of a manipulation attempt using more than half the processing power of the network, see Garratt and Hayes (2014), Budish (2018) and Auer (2019).
8 For an overview of the concepts behind and the uses of blockchain technology, see Federal Office for Information Security (2019).
9 According to estimates from the Cambridge Centre for Alternative Finance from May 2021, total energy consumption for Bitcoin payment validation stands at 144 TWh per year, roughly the total energy consumption of the Netherlands. See also De Vries (2018). One factor in the high energy consumption is the price of Bitcoin itself. As described below, miners are remunerated in Bitcoin and compete to find solutions to cryptographic puzzles. When Bitcoin prices rise, this creates incentives to invest in higher processing power, which in turn leads to the difficulty of the cryptographic puzzles being raised – and thus increases the energy consumption required to find the solution.
10 The conceptual analogy to mining for raw materials explains the "miner" nomenclature. Economic analyses of miners' incentives can be found in, amongst others, Ma et al. (2018) and Prat and Walter (2021).

Simplified illustration of the Bitcoin blockchain



Source: Bundesbank depiction based on Auer (2019). **1** The hash input is made up of three components: the hash output of the previous block, data derived from the transactions, and the nonce. **2** Digitally signed transactions are collected by miners and arranged into blocks. **3** Character string that must be found by miners via trial and error such that the hash output meets the requirements. **4** Derived from the hash input. Must start with a specific number of zeros in order for a block to be accepted by the network. **5** As one component of the hash input is the output of the previous block, this creates a chain. Any change to an already-accepted block would mean the solutions for all the following blocks would need to be found again from scratch.

Deutsche Bundesbank

Examining the creation of new bitcoins reveals another important, unique element of the Bitcoin protocol. The rules set out roughly how long it takes to add a new block to the chain and how many bitcoins are earned for each block. The target is for a solution to a cryptographic puzzle to be found and a new block added to the chain roughly every ten minutes. To achieve this, the difficulty of the cryptographic puzzle is regularly adjusted – once every 2,016 blocks, to be precise.[11] If a lot of processing power is invested by miners over a period of time, increasing the speed at which cryptographic puzzles are solved, the requirements for the hash function output are made stricter – increasing the expected amount of time needed to find the solution. The difficulty is lowered, on the other hand, when adding new blocks has repeatedly taken longer than ten minutes on average. The number of new bitcoins that are created for each block is also periodically reduced, being halved every 210,000 blocks.[12] When the network was created in 2009, the number of bitcoins created per block was 50. This was reduced to 25 at the end of 2012 and to 12.5 in mid-2016. Since mid-2020, the block reward rate has been 6.25 bitcoins. The rules thus ensure that the supply of Bitcoin grows in a very predictable manner while being limited in the long term. Extrapolating this process into the future, the result is that there will never be more than 21 million bitcoins in existence.[13]

11 Roughly once every two weeks.
12 Roughly once every four years.
13 This limit will be reached in or around the year 2140, although more than 18 million bitcoins have already been created. Of course, it is not inconceivable that the source code into which the 21 million bitcoin hard cap is encoded could be changed in the future. This already occurred when disputes amongst users led to a hard fork in 2017, where one part of the network was split off in order to increase the number of transactions per time unit. It is certainly possible that another such hard fork might occur due to disagreement over the total number of bitcoins or the creation of new bitcoins. While the original version of the protocol could continue to operate indefinitely, if market participants prefer the other version overall, the original token could become less important.

participants and are publicly viewable in pseudonymised form.[6] This aims to prevent dependency on individual institutions at the heart of the system whose actions and continued existence would have to be relied upon.

… with a mechanically increasing, finite supply of tokens in circulation …

A second point concerns the management of the supply of tokens in circulation, which, in the case of Bitcoin, is mechanically linked to adding transaction blocks to the payment register and is therefore largely predictable. At the same time, it is stipulated that the issuance of Bitcoin will slow down over time and ultimately stop entirely, meaning that the total amount of bitcoins that will ever exist under the current ruleset is finite.[7]

In this respect, Bitcoin is comparable to other physically limited assets and means of payment.[8] The rules governing its supply do not allow for any discretionary interventions. By contrast, central banks can adjust their monetary policy stance as necessary and largely at their own discretion, thereby influencing the value of their issued currency – for instance, with the aim of maintaining price stability and preventing value fluctuations such as those typical for Bitcoin.

… without central issuers or collateral backing

Finally, the lack of an issuer is another difference between Bitcoin and conventional assets. For example, there is no central entity against which a holder of Bitcoin could assert a legal claim. In fact, holding crypto tokens means nothing more than having a record in the network's payment register stating that units of value were transferred to the current holder at a previous point in time. Holders of tokens must therefore trust that the system will not be compromised and that they will not lose access to their own tokens, since it would not be possible to assert a claim in such a scenario. Bitcoin is not backed by collateral and holding the token is not associated with any returns, such as interest payments on bonds or dividends on shares.

Numerous crypto tokens with different characteristics, …

In addition to Bitcoin, there are now a wide variety of other crypto tokens, which are referred to as "altcoins".[9] Depending on their design, these tokens can be very similar to Bitcoin in some cases or differ considerably in certain aspects (see the box on pp. 68 ff.). However, one thing many of the most important tokens in terms of market capitalisation have in common is that units of value are transferred in a decentralised manner and, although the amount in circulation is not necessarily finite, it grows mechanically without a central entity having discretion to make decisions about this.

… but Bitcoin still by far the most significant token

Despite the large number of altcoins, Bitcoin still remains by far the most significant token – this is referred to as Bitcoin dominance (see the box on pp. 71 f.). For these reasons – and because Bitcoin, as the first crypto token, was conceived in response to aspects of the existing financial system that were perceived by some observers as problematic – this article largely focuses on Bitcoin as well as on some other major tokens with similar designs.

Price developments of crypto tokens

The special characteristics of crypto tokens outlined in this article also have an impact empirically.[10] For instance, their market prices often behave differently to those of conventional

6 Transfers of Bitcoin take place between public keys (see the box on pp. 63 ff.), meaning that the identities behind the keys cannot be inferred directly.
7 However, in principle, it is conceivable that the ruleset could undergo changes in future, although this would require consensus amongst users to amend the protocol in this regard. See the box on pp. 63 ff.
8 In the eyes of some users, the mechanical supply of Bitcoin is similar to that of naturally occurring commodities such as gold. In this case, too, supply is growing in a relatively predictable way as a result of mining, but the total available amount of gold in existence on earth is limited. This association is also reflected by the term "Bitcoin mining" – just like the mining of commodities, it generates costs and consumes a large amount of resources. As explained on pp. 63 ff., however, this use of resources does not actually serve to create new bitcoins, but instead is intended to protect the blockchain, i.e. the payment register, against manipulation.
9 Short for "alternative coins".
10 An overview of the empirical literature on the prices of crypto tokens can be found in Corbet et al. (2019).

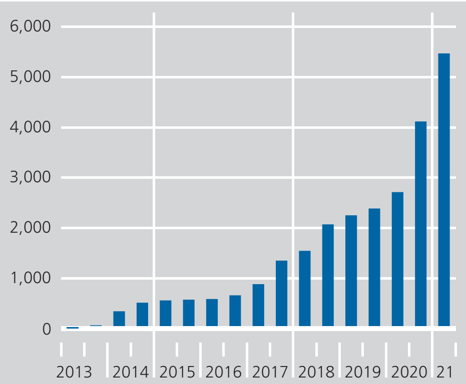
Other crypto tokens: altcoins

In addition to Bitcoin, there are a wide array of other crypto tokens known as altcoins.[1] The chart below illustrates the number of crypto tokens listed over time on www.coinmarketcap.com. After a period of little movement up until the end of 2017, the number of new tokens then rose sharply – chiefly on the back of the steep increase in the Bitcoin price. At last count, there were well over 5,000 different crypto tokens; yet, measured in terms of market capitalisation, many of these are of minor significance.[2]

One reason for the creation of new crypto tokens is the emergence of novel blockchain solutions that, for instance, are capable of processing a larger number of transactions, consume less energy or use a more complex computational logic than the Bitcoin blockchain.[3] These solutions vary in terms of the cryptographic hash functions used or the scale and frequency of new transaction blocks, whilst others have fundamentally different rules for validating transactions.[4] In some cases, these differences in design are an attempt to address the characteristics of Bitcoin that are considered problematic.[5]

Number of recorded crypto tokens*

Semi-annual figures



Source: CoinMarketCap. * Number of crypto tokens listed on coinmarketcap.com with data on market capitalisation.
Deutsche Bundesbank

For instance, Bitcoin Cash (BCH) was the product of a hard fork of Bitcoin created in 2017 and designed to increase the size of transaction blocks from one to eight megabytes.[6] This was to address the lack of scalability in the Bitcoin blockchain – i.e. the problem that only a very limited number of transactions could be processed within a certain period of time,[7] which can lead to delayed transactions and high transaction costs.[8] Previously, Litecoin had taken a different route by opting to generate its transaction blocks every two and a half minutes rather than every ten minutes as with Bit-

1 Short for alternative coins. For more details on their place in the development of crypto tokens, see also Deutsche Bundesbank (2017b, 2019, 2021).
2 CoinGecko's website even lists more than 8,000 tokens. CoinMarketCap, the source of the information on which this chart is based, also counts over 10,000 in total. However, it only provides figures on market prices and market capitalisation for the just over 5,000 tokens included in the chart.
3 Furthermore, a number of blockchain solutions support the issuance of more than one type of crypto token, which can then be transferred via the blockchain in question. This means that it is not always necessary to program a dedicated blockchain to issue a new crypto token.
4 For an explanation of terms such as "cryptographic hash function", "transaction block" or "validation", see pp. 63 ff.
5 By contrast, other market participants believe that the true strength of Bitcoin actually lies in some of these perceived weaknesses, such as the resource-intensive consensus mechanism.
6 This was the result of a major dispute in the Bitcoin community – the "block size wars" – which resulted in the blockchain being hard-forked, i.e. split into two ledgers. These two ledgers now coexist separately but, prior to the split, shared the same transaction history. For an overview of other hard forks in crypto tokens, see Soiman et al. (2021).
7 A maximum of around seven transactions can be validated each second – a fraction of the volume that existing payment systems can manage.
8 Average transaction fees can run to in excess of US$50, especially when network utilisation is high. At quieter times, fees are well under US$1. For an economic analysis of transaction fees, see Easley et al. (2019) and Huberman et al. (2020).

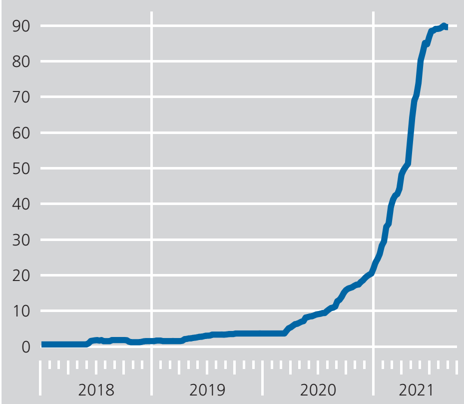
coin, thus quadrupling the number of transactions that can be validated.[9]

Other blockchains try to make up for the lack of scalability, a problem inherent in the Bitcoin blockchain, by using an alternative consensus mechanism such as proof of stake (PoS). In contrast to proof of work (PoW), the probability of a validator being selected is proportional not to their computational power but rather the amount of crypto tokens they lock up for this purpose (staking).[10] A common feature of the two consensus mechanisms is, then, that the more system participants have invested – be it in terms of computational power and specialised hardware for PoW or in terms of owning and staking crypto tokens for PoS – the greater the number of new transactions they can validate.[11] In other words, both mechanisms are based on the idea that the more participants themselves are involved in the system, the lower their incentive to manipulate it and the more expensive manipulations would be for third parties. Supporters of PoW sometimes argue that PoS is not as safe. However, as PoS does not involve mining, it consumes much less energy. The best-known blockchains developed using the PoS approach are Cardano, Solana, Algorand and Tezos. Efforts are also under way to convert existing blockchain solutions to PoS.[12]

Furthermore, blockchains have been developed over the course of time that have additional functions compared with the Bitcoin blockchain. The best-known example is the Ethereum blockchain, which was launched in 2015.[13] On the Ethereum blockchain, the execution of transactions can be "programmed" using complex smart contracts. Such contracts can be used to automatically execute complex use cases, which can sometimes lead to the creation of decentralised financial applications.[14]

Market capitalisation of stablecoins

€ billion, weekly data



Source: CoinCodex.
Deutsche Bundesbank

One important category of crypto tokens is stablecoins.[15] Unlike other tokens where prices fluctuate according to supply and demand, with stablecoins the aim is to keep

9 In 2018, the BCH block size was increased again to 32 megabytes. Other market participants use innovations in the Bitcoin network itself to address the problem of a lack of scalability. One example is the Lightning Network, which enables private payment channels to be opened between peers, with the blockchain itself being used only to validate their balances; see Divakaruni and Zimmerman (2020).
10 For a formal microeconomic analysis of PoS, see Gans and Gandal (2019).
11 With PoS, the probability of being selected is based on the number of coins that a potential validator is prepared to lock up for a certain time. These coins serve as a security of sorts for the network. In proven cases of rule-breaking, the validator's coins are destroyed as a way of incentivising honest behaviour.
12 The Ethereum Foundation, for one, is planning on making the switch for the Ethereum network described below.
13 See Buterin (2013).
14 For a detailed description of decentralised financial applications, including the challenges and risks that they pose, see Deutsche Bundesbank (2021).
15 See Arner et al. (2020).

the price stable.[16] Most existing stablecoins try to keep their exchange rate at par with the US dollar. Others are pegged to the euro or other currencies, precious metals such as gold, or a basket containing several assets.

The chart on p. 69 shows the market capitalisation of existing stablecoins.[17] In contrast to crypto tokens with fluctuating prices, growth in market capitalisation is not primarily a reflection of valuation effects. If there is demand for additional stablecoins, new tokens have to be generated in order to keep the price constant. As supply thus responds fully elastically to demand, growth in market capitalisation means an increase in the number of tokens in circulation. In comparison to the overall market for all crypto tokens, however, the market for stablecoins is still small (just over 5% at the end of August 2021). Nevertheless, measured in terms of transaction volume on both crypto exchanges and decentralised trading platforms, stablecoins are playing an increasingly important role.[18]

16 There are various approaches to trying to maintain price stability. These include backing the tokens with liquid funds from precisely those assets against which the price of the stablecoin is to be kept stable, as well as algorithms. In practice, it is not always possible to keep the price stable, and the value of some stablecoins has already drifted far from their target price. For an economic analysis of the stability risks associated with stablecoins and of issuers' incentives, see Li and Mayer (2020), Klages-Mundt et al. (2020) and d'Avernas et al. (2021). Gorton and Zhang (2021) offer an account of how stablecoins fit into the history of money and finance.
17 The underlying data are from private websites. As a result, they are less reliable than data from official institutions but nonetheless give a rough overview of conditions and are often used even in academic research; see, for example, Bouri et al. (2017a) and Liu and Tsyvinsky (2018).
18 According to Chainalysis (2021), stablecoins accounted for the largest transaction volume of all crypto tokens in the first quarter of 2021.

assets, particularly with respect to their susceptibility to fluctuations in value.

Market prices of crypto tokens exhibit gains in value …

The market prices of Bitcoin and other major tokens that have existed for many years, such as Ether and Litecoin, show an upward trend in market value overall. However, their market price movements also exhibit numerous distinct cycles. In these boom and bust phases, the token prices appreciate strongly within a relatively short period of time, and then lose a large share of their increase in value again.

… high volatility …

In order to gain a sense of the degree to which crypto tokens fluctuate in value, a comparison with the prices of other assets can be made, for example, by looking at the volatility of daily returns – a measure of the typical percentage changes in returns from day to day.[11] On average over recent years, the daily return on risky shares – for example, for an index of the largest publicly listed corporations in terms of market capitalisation in the euro area – fluctuated by around 1 percentage point over the period of one day. Return fluctuations were slightly lower in the case of gold, and the rate of change in the euro/US dollar exchange rate typically fluctuated by just less than ½ percentage point. By contrast, the volatility of crypto tokens was many times higher. While the returns on Bitcoin fluctuated in value by around 4 percentage points, the average daily shift in the value of Ether and Litecoin was even greater at around 6 percentage points. And even these considerably higher figures apply only to an average day. This means that they obscure the fact that, in the past, the market prices of the crypto tokens mentioned above rose or fell by several dozen percent multiple times within the space of just one day.

However, not only are the market prices of tokens exceptionally volatile, but the returns on

11 Calculated as the standard deviation of the daily percentage value changes in the analysed assets.

The dominance of Bitcoin in the market for crypto tokens

The market for crypto tokens has grown significantly over recent years. In the first few years following the introduction of Bitcoin, the market capitalisation of all tokens – i.e. the number of tokens in circulation multiplied by their prices, expressed in euro – amounted to just a few billion euro; over the course of 2017, it grew rapidly and exceeded €600 billion for the first time in December of that year. Market capitalisation then declined in 2018, but rose again sharply at the end of 2020, reaching a record high of almost €2 trillion in May 2021.[1]

First and foremost, this development is a reflection of valuation effects: the total market capitalisation of all tokens fluctuates primarily in line with the market values of individual tokens. Another driver of this market growth is the fact that new crypto tokens are constantly being created. In the first few years following the introduction of Bitcoin in January 2009, only a few new coins emerged – including Litecoin, Ripple and Ether – however, especially after the sharp rise in prices at the end of 2017, a large number of new crypto tokens entered into the market.[2]

While Bitcoin still represented more than 90% of market capitalisation in 2014, its market share dropped to less than 40% for a time during the course of 2017. The shares of newer, smaller crypto tokens grew to more than 20%, and other already established tokens, such as Ether, also gained ground. Although there were then thousands of crypto tokens in existence at that point, Bitcoin remained the most significant by a considerable margin. As a result, Bitcoin's sole share of the total market grew again from 2018, standing at 44% at the end of August 2021 – this is referred to as Bitcoin dominance.[3]

Alongside market capitalisation, trading volumes on crypto exchanges are an additional indicator that can be used to assess the significance of the market as a whole as well as of individual crypto tokens. There are a number of websites that provide figures on the aggregate trading volume across the many crypto trading platforms where crypto tokens can be exchanged for traditional currencies or for each other. Depending on the crypto token in question, these figures on trading volumes amount to several billion euro per day, but are often believed to be considerably

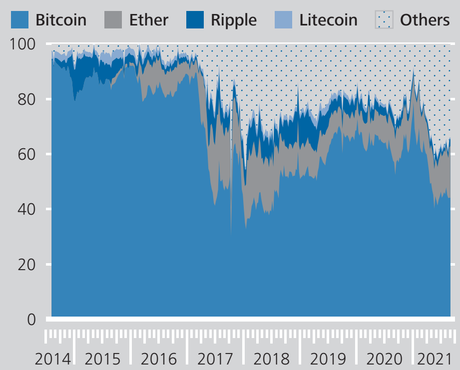
Market capitalisation of crypto tokens

€ billion, weekly data

Source: CoinMarketCap.
Deutsche Bundesbank

Shares of selected crypto tokens in total market capitalisation

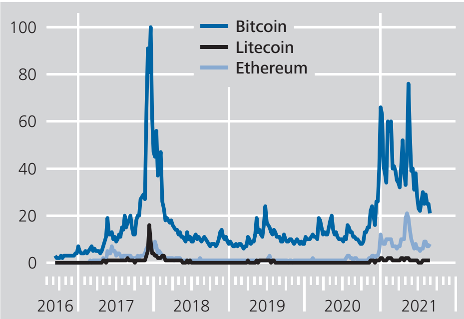
%, weekly data



Sources: CoinMarketCap and Bundesbank calculations.
Deutsche Bundesbank

1 The underlying data are from private websites. To this extent, they are less reliable than data from official institutions, but provide a rough overview of the prevailing conditions. Reference is frequently made to these data.
2 An overview of this is provided in the box on pp. 68 ff.
3 Gandal and Halaburda (2016) analyse competition between crypto tokens and investigate the extent to which network effects benefit Bitcoin as the oldest token.

Google search queries for selected crypto tokens*



Source: Google Trends. * Worldwide internet search queries for the terms "Bitcoin", "Litecoin" and "Ethereum" using the Google search engine; figures relative to the maximum number of search queries for "Bitcoin" in December 2017 (= 100).
Deutsche Bundesbank

overstated.[4] Nevertheless, analysing the shares of each traded crypto token can provide some indication of their relative significance. As before, this shows the market dominance of Bitcoin with a market share of around 34%, followed by Ether with approximately 26%.[5]

Finally, the dominance of Bitcoin can also be seen in the public interest in various crypto tokens, for example, as measured by the relative frequency of worldwide search queries using the Google search engine. Here, a distinction is made between the term "Bitcoin" and the terms "Litecoin" and "Ethereum". The figures are stated relative to the maximum level of search interest for "Bitcoin", which was recorded in December 2017. The adjacent chart clearly shows that Bitcoin is dominant in the public perception, too.

4 According to estimations, a substantial proportion of the reported trading volume on the major crypto trading platforms consists of what are known as "wash sales"; see Cong et al. (2021) and Aloosh and Li (2021). In these sales, investors issue buy and sell orders at the same time in order to create artificial trading volume on the crypto trading platforms. Reported trading volumes play a role, for example, when crypto trading platforms compete for market share and transaction fees.
5 This is based on the figures provided by CoinMarketCap for the trading volumes in a 30-day period from mid-July to mid-August 2021. Stablecoins, which are often used to exchange between crypto tokens, are not taken into consideration here.

… low correlation with other assets …

the major tokens also show no systematic correlation with those of conventional assets. For instance, the returns on the three crypto tokens mentioned above barely correlate with those of shares or exchange rates: the respective correlation coefficients are close to zero. The correlation with gold is only slightly higher.

… but greater co-movement with one another

By contrast, the relationships between the three crypto tokens analysed in this context reveal a completely different picture. The correlation here is considerable – the coefficients are greater than 0.5 and thus relatively high. Token prices therefore tend to move in tandem over the course of a day, but behave differently to those of shares, exchange rates or precious metals. In fact, academic studies show that crypto tokens have risk-return relationships that have differed fundamentally from those of conventional assets in the past.[12]

Conceptual considerations regarding the impact of monetary policy on crypto tokens

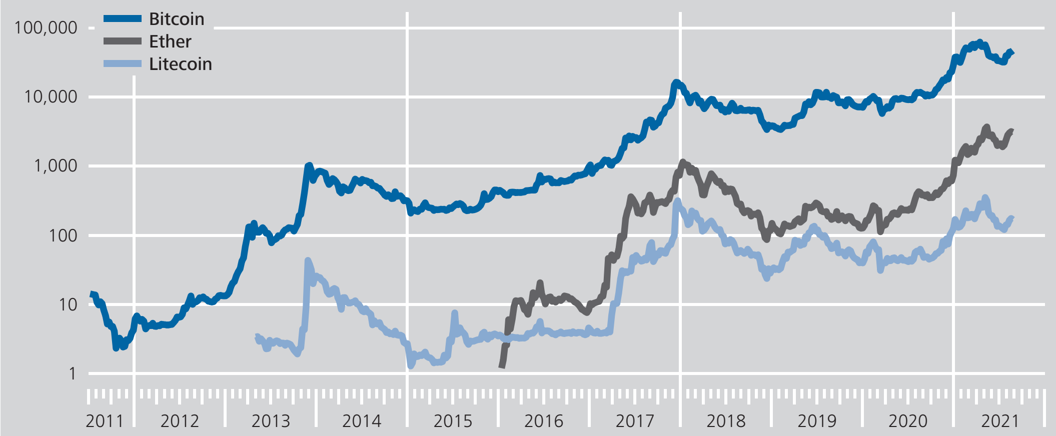
Monetary policy expected to have impact on asset prices, e.g. for shares …

A large body of literature on economics investigates how the market prices of various assets are determined. Theoretical considerations suggest that share prices, for example, are dependent on the expected future profits of the issuing enterprise and on the interest rate used to discount these profits distributed as dividends. This means that changes in monetary

12 Liu and Tsyvinski (2018) analyse the extent to which the prices of the three crypto tokens Bitcoin, Ripple and Ether are dependent on determining factors that are often employed in empirical economic research to explain returns on shares, for example. The authors come to the conclusion that the correlations detected for other asset classes do not apply to the crypto tokens mentioned above. Instead, they identify crypto token-specific determining factors, such as with regard to past returns on tokens (momentum factor). Using various criteria, Ankenbrand and Bieri (2018) confirm that crypto tokens represent their own asset class that differs in a variety of ways from conventional assets.

Market prices of selected crypto tokens*

US$, log scale



Sources: CoinMarketCap and Bitcoinity. * Values shown from a market price of US$1.
Deutsche Bundesbank

policy should affect share prices in at least two ways: if, for example, the central bank lowers its policy rate or communicates a lower future interest rate path, expected corporate profits will be discounted to a lesser extent, mechanically increasing their present value. In addition, if the interest rate cut also stimulates general economic activity, profit expectations themselves might also improve, which would likewise result in higher share prices.

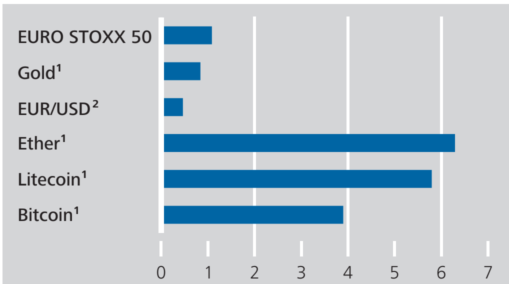
… and exchange rates

Monetary policy impulses also affect exchange rates, i.e. the relative price of two currencies. According to theory, the exchange rate between a pair of currencies should depend largely on the relative levels of interest rates in the two currency areas.[13] If, for instance, interest rates in the euro area were to fall, some of the demand for interest-bearing securities would possibly shift to the United States, provided that interest rates were not also falling there. Accordingly, there would be greater demand for the US dollar and lower demand for the euro – the single currency would hence depreciate against the US dollar.[14]

Monetary policy likely has direct impact on prices of crypto tokens expressed in euro …

It stands to reason that monetary policy impulses from the Eurosystem should have an effect on the euro prices of crypto tokens, too. Just as the euro would depreciate against, say, the US dollar if the Eurosystem were to loosen its monetary policy stance (i.e. the price of the US dollar would rise measured against the euro), it can be assumed that the euro prices of other assets and goods would also increase, in-

Volatility of returns of selected crypto tokens and conventional assets*



Sources: CoinMarketCap, ECB and Bundesbank calculations. * Average standard deviation of percentage value changes in the analysed assets. Sample period: August 2015 (initial listing of Ether) to June 2021. Figures from March 2020 were excluded from the calculation in view of the market crash during the COVID-19 crisis. **1** On US dollar basis. **2** Euro/US dollar exchange rate.
Deutsche Bundesbank

13 This relationship is described in the economic literature by the theorem of (uncovered) interest parity, which states that the expected return on a secure investment in domestic currency must be same as that on an equivalent secure investment in foreign currency. If the nominal returns differ between the two currency areas, an expected change in the exchange rate ensures that the expected returns balance out. For further details on this, see Deutsche Bundesbank (2005). Dedola et al. (2020) describe these and other theoretically derived determinants of the exchange rate.
14 For a detailed analysis of the impact of monetary policy on the euro's exchange rate, see Deutsche Bundesbank (2020).

Correlation of selected crypto tokens with one another and with other assets*

	Bitcoin[1]	Ether[1]	Litecoin[1]	Gold[1]	EUR/USD[2]
Ether[1]	0.51				
Litecoin[1]	0.67	0.52			
Gold[1]	0.09	0.08	0.07		
EUR/USD[2]	0.04	0.06	0.03	0.15	
EURO STOXX 50	0.04	0.02	0.04	-0.20	-0.01

Sources: CoinMarketCap, ECB and Bundesbank calculations. * Darker colours indicate greater correlation. Sample period: August 2015 (initial listing of Ether) to June 2021. Figures from March 2020 were excluded from the calculation in view of the market crash during the COVID-19 crisis. **1** On US dollar basis. **2** Euro/US dollar exchange rate.

Deutsche Bundesbank

cluding the euro price of Bitcoin. As long as Bitcoin can be traded internationally against various currencies with only minimal friction, the euro price and the US dollar price of the token converted into euro at the current exchange rate should only differ marginally during the adjustment process. Otherwise, it would be possible to conduct arbitrage transactions.[15]

… but further effect on crypto tokens less obvious a priori

However, why the price of Bitcoin in US dollar should also change is less obvious at first. Unlike bonds, Bitcoin does not promise to pay any interest, and unlike shares, it promises no dividends that would increase or be less heavily discounted as a result of monetary policy easing. Furthermore, Bitcoin is still not widely used as a means of payment in day-to-day economic life, so it stands to reason that its value should not be driven primarily by the level of economic activity, which monetary policy easing is intended to stimulate.[16]

Notion of Bitcoin as protection against inflation could bring about monetary policy effects …

Instead, the effects of monetary policy on token prices could be rooted in the claim that holding Bitcoin supposedly protects against inflation. If monetary policy easing makes the hypothetical scenario of a rapid decrease in the euro's purchasing power more probable in the eyes of individual market participants, they may seek to invest primarily in assets not subject to discretionary decision-making regarding their supply. The Bitcoin price would then benefit to an especially large extent from monetary policy that is perceived as excessively expansionary.[17]

… as could search for yield …

Lastly, the high valuation levels of crypto tokens are sometimes also seen simply as an expression of speculative excesses, which are supposedly attributable to, amongst other things, loose monetary policy. Due to the fact that, in some cases, even risky bonds do not offer positive interest rates, investors may increasingly consider highly speculative assets in their search for yield and hope for further price gains.[18] So, given that crypto tokens do not promise any returns and are also not widely used as a means of payment, their high market prices can be best explained by a surge in liquidity triggered

15 Investors would buy Bitcoin at a low price in euro, sell it at a higher price in US dollar, and then exchange the acquired US dollar currency back for the depreciated euro. In fact, the prices of crypto tokens in different currencies are not entirely immune from what are ostensibly arbitrage opportunities. For example, there may be persistent differences between the US dollar price of Bitcoin and its price (converted into US dollar) in other currencies, especially those of developing countries and emerging market economies. These price differences reflect frictions in the aforementioned adjustment process, which can stem from factors such as transaction costs and capital controls or from risks arising from the high volatility of prices; see Kroeger and Sarkar (2016) and Makarov and Schoar (2020). In the past, the price difference has been particularly pronounced for the Korean won; see Choi et al. (2020). By contrast, the differences between the US dollar and euro prices of Bitcoin are usually very small, and the arbitrage transactions described above are primarily for illustrative purposes.
16 For example, Liu and Tsyvinski (2018) find no evidence that Bitcoin's market value is dependent on macroeconomic activity.
17 It is possible that an effect of this kind would be felt primarily at significantly higher inflation rates than those observed in the recent past. Such a non-linear effect would be more difficult to prove on the basis of historical data. For more details on the fundamental problem of proving the causal effects of monetary policy impulses, see the relevant section of this article on pp. 77 f.
18 See Rajan (2005) and Borio and Zhu (2012). This behaviour is documented, in particular, for financial institutions such as banks or money market and pension funds; see, for example, Jiménez et al. (2015) and Di Maggio and Kacperczyk (2016). But there is also evidence to suggest that households are searching for yield by rebalancing their portfolios in favour of more profitable forms of investment; for the case of Germany, see, for example, Deutsche Bundesbank (2016a). If asset prices rise, financial market participants might also reckon with decreasing probabilities of loss, which is why a loose monetary policy stance could help encourage them to take on additional risks; see, for example, Deutsche Bundesbank (2016b).

by monetary policy, which drives up the market prices of all kinds of risky assets.[19]

… but hypotheses require empirical testing

Therefore, if speculation fuelled by monetary policy or concerns about future inflation are indeed major factors driving the performance of Bitcoin and other crypto tokens,[20] it would be expected that their prices respond sensitively to monetary policy impulses. The extent to which this is the case is examined below.

Insights into the significance of Eurosystem monetary policy for crypto tokens

Empirical literature looks at asset price responses in narrow time windows around monetary policy decisions

In order to get a sense of whether and how monetary policy decisions affect asset prices, the economic literature often looks at the responses of these prices in narrow time windows around the announcements of monetary policy decisions.[21] If, for example, share prices rise immediately after a monetary policy announcement is made, but move sideways beforehand and afterwards, it can be plausibly concluded that the increase is primarily attributable to the monetary policy impulse. Indeed, there is ample empirical evidence that the prices of bonds, shares and foreign currencies often respond immediately and significantly to monetary policy decisions.[22] Initial insights into the effect of Eurosystem monetary policy on crypto tokens could therefore be gained by expanding this type of analysis to cover token prices, as described below. In this context, the currency in which crypto token prices are expressed is key. Given that, as stated above, the effect on token prices expressed in euro is hardly surprising and Bitcoin is mainly traded against the US dollar, token prices are expressed exclusively in US dollar in the following analysis.

Bitcoin price tends to be more volatile around monetary policy announcements …

First, the average return volatility of Bitcoin and other assets in the time windows around the announcements of monetary policy decisions by the ECB Governing Council is examined. The period analysed begins 15 minutes before the ECB press release is published at 13:45 and lasts until 75 minutes after the subsequent press conference starts at 14:30, spanning all in all from 13:30 to 15:45. Studying these short time periods, it turns out that the already volatile Bitcoin prices are, on average, just over 10% more volatile than in comparable time windows on normal afternoons on which no monetary policy announcements are made. This finding could indicate that monetary policy decisions are also important to crypto token markets because they lead to unusually large price swings. However, the difference between days with monetary policy announcements and those without is not statistically significant, at least if days with extreme value fluctuations are included in the analysis.[23]

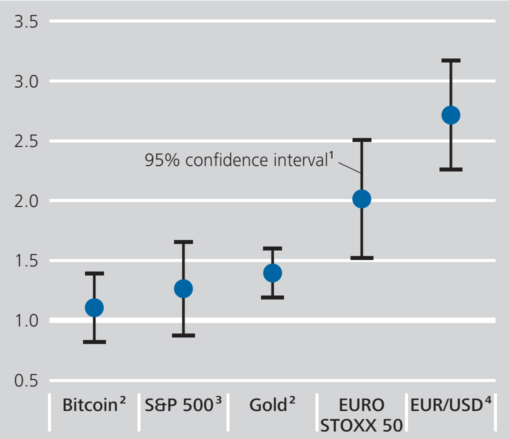
… but increase in volatility of share prices and exchange rates greater and also statistically significant in these windows

Further information can be gleaned by comparing these results with equivalent calculations for the gold price, the euro/US dollar exchange rate and the stock price indices S&P 500 (for the United States) and EURO STOXX 50 (for the euro area). It transpires that some of these returns experience considerably larger increases in volatility in the time windows around the announcements of monetary policy decisions. For example, the average volatility for the EURO STOXX 50 is twice as high as usual, while that

19 See, for example, Bloomberg (2021).
20 According to De Haan and van den End (2017), there is a connection here. In the past, unusually high asset prices were often also an indicator of high future inflation rates.
21 Kuttner (2001) and Gürkaynak et al. (2005) were among the first studies to propose this approach, which has since become established practice. Generally, all scheduled meetings of the relevant monetary policy decision-making body are taken into account, irrespective of the announcements made. In particular, whilst a monetary policy decision need not necessarily be related to a change in policy rates or asset purchase programmes, all monetary policy communication within a narrow time frame around press releases and press conferences following the meetings is analysed.
22 See Zettelmeyer (2004), Bernanke and Kuttner (2005), Altavilla et al. (2019), Gilchrist et al. (2019), Deutsche Bundesbank (2017a, 2020) and Gürkaynak et al. (2021).
23 The difference amounts to around one-third and is statistically significant if the most volatile 10% of all days are excluded when calculating the values. There have been extreme fluctuations in the price of Bitcoin on a number of days in the past. By excluding these particularly volatile movements, it is thus possible to compare more "ordinary" days with those on which monetary policy announcements were made.

Yield volatility growth in time windows around announcements of monetary policy decisions*

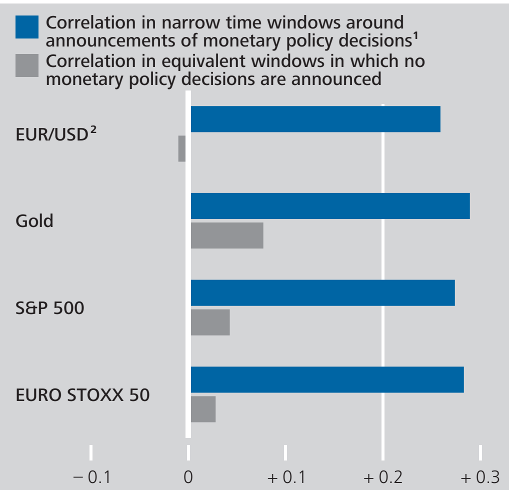
Factor



Sources: Tickstory, Bitcoincharts and Bundesbank calculations. * Average standard deviation of percentage value changes in the analysed assets based on data taken at five-minute intervals in the time windows around the announcements of monetary policy decisions by the ECB Governing Council (15 minutes before the start of the press statement to 75 minutes after the start of the subsequent press conference). Values given relative to equivalent windows on days on which no monetary policy decisions are announced. Sample period: January 2015 to June 2021. **1** 95% confidence bands based on t-tests to compare mean values inside and outside the monetary policy window. **2** On US dollar basis. **3** Over-the-counter (OTC) trading. **4** Euro/US dollar exchange rate.

Deutsche Bundesbank

Correlation of yields from Bitcoin and conventional assets in time windows around announcements of monetary policy decisions*



Sources: Tickstory, Bitcoincharts and Bundesbank calculations. * The sample period spanned from January 2015 to June 2021. Adjusted for several days on which the analysed assets were subject to extreme value fluctuations (20 July 2017 and 12 March 2020 in the case of Bitcoin and 22 October 2015 and 3 December 2015 in the case of EURO STOXX 50). **1** 15 minutes before the start of the press statement to 75 minutes after the start of the subsequent press conference. **2** Euro/US dollar exchange rate.

Deutsche Bundesbank

of the euro/US dollar exchange rate is just over two and a half times as high. These differences are each statistically highly significant. The increases in return volatility for gold and the US stock price index S&P 500 are only somewhat higher than that for Bitcoin. However, at least for gold, the corresponding confidence intervals show that the increase in return volatility is subject to a lower degree of uncertainty than that for Bitcoin.

Bitcoin price more strongly correlated with other asset prices in time windows around monetary policy decisions

A similar comparison can be made with respect to the second characteristic of crypto tokens discussed above: their low correlation with the market prices of other assets. To this end, one can look at correlation coefficients between the returns on Bitcoin and those on stock price indices, gold and the euro/US dollar exchange rate in the aforementioned narrow time windows around monetary policy announcements by the ECB Governing Council. It turns out that the co-movement of returns is higher than normal, with correlation coefficients increasing from below 10% to almost 30%.[24] In this comparison, too, however, the increase is not statistically highly significant in all cases and it is lower than the increased correlation between stock price indices and exchange rates, for example – by way of illustration, the correlation between the EURO STOXX 50 and the euro/US dollar exchange rate amounts to around 60% within the monetary policy time window.

In summary, the findings so far indicate that monetary policy decisions could also be of relevance to crypto tokens such as Bitcoin. At the same time, the relative influence of monetary policy on the market prices of shares, precious metals and foreign currencies appears at first glance to be more significant. However, the previous analysis only considers the immediate responses of different asset prices to monetary policy announcements. The already very high

24 However, correlation with the EURO STOXX 50 is less than 20% if the analysis includes 22 October 2015, the date on which Bitcoin's value increased by just under 2% shortly before the Governing Council's monetary policy announcement.

volatility of crypto token prices could make it difficult to unambiguously demonstrate any impact of monetary policy within these short periods of time. What is more, the markets for crypto tokens are also less liquid than those of many conventional assets, which could further limit the informative value of an analysis based on high-frequency data alone. The question therefore arises as to whether any systematic impact of monetary policy can also be determined over longer periods and whether monetary policy impulses can explain a quantitatively significant portion of the movements in crypto token prices over time. Answering such questions requires econometric models that allow causal statements to be made about the dynamic effects of monetary policy impulses.

Econometric analyses on the causal effect of monetary policy impulses on crypto tokens

Differentiating monetary policy impulses from other determinants is crucial …

In order to be able to examine the impact of monetary policy on financial market prices and other variables over time, it is necessary to distinguish monetary policy impulses from other potential driving forces. Whilst in the high-frequency analysis an immediate market response to ECB announcements could plausibly be attributed primarily to monetary policy impulses, this is not the case over longer periods of time.

… but fraught with challenges

The problem can be illustrated by means of the following example: as many central banks around the world are committed to price stability as part of their mandate, their aim is to stabilise the inflation rate at a low level. At least in the short term, however, the inflation rate is determined by many factors besides monetary policy, such as events on international commodity markets or wage agreements impacting the prices of firms' intermediate goods or labour costs. If the central bank were to anticipate increasing price pressures overall, it would raise interest rates in order to counteract rising inflation. If the central bank succeeds in keeping the inflation rate stable at close to its target in the months that follow, however, it cannot be concluded that the interest rate increase had no effect on the price level – after all, without monetary policy adjustment, inflation would have risen as expected. And even if the central bank were to react too tentatively, i.e. if the inflation rate were to increase somewhat, it would be wrong to arrive at the conclusion that interest rate hikes instead cause prices to rise rather than fall. In order to draw any conclusions regarding the causal effect of a monetary policy impulse, then, it is not enough to simply examine how certain variables behave over longer intervals after a monetary policy instrument is altered.

Econometric models enable identification of monetary policy shocks

In order to solve these problems, the economic literature has developed econometric models that enable structural shocks to be identified. In these models, the many observable potential determinants that can influence prices and other economic variables are broken down into individual, clearly differentiated components (shocks). When it comes to monetary policy, this means that the models attempt to isolate the component – such as a change in interest rates – that does not simply represent a response by the central bank to other exogenous factors, but one where it actively intervenes. If this is successful, the models are able to isolate the causal effect of monetary policy on individual variables over time and determine its relative significance.

Frequent use of VAR models …

Vector autoregressive (VAR) models are often used for this purpose. As a first step, statistical estimations are performed to assess how different variables are connected and interact with each other over time. Some of the changes in each individual variable can then be traced back to preceding developments in all of the other variables. However, another part will remain unexplained by the model structure, i.e. the estimated interdependencies of the variables, and it is this component that forms the basis for identifying the aforementioned structural shocks.

… supplemented by information from outside the model

A number of different methods have been developed over time for this purpose, and approaches that draw on information from outside the model are becoming increasingly popular, especially for identifying monetary policy shocks. Proxy VAR models, for example, make use of instrumental variables,[25] which often include the responses of short-term interest rates within narrow time windows around monetary policy announcements. Somewhat similar to the immediate responses of other financial market variables outlined above, it is plausible that such changes to short-term interest rates are predominantly triggered by monetary policy decisions or announcements, whilst other determinants are likely to have hardly any effect. The interest rate responses also indicate that, to at least some extent, these decisions were not expected by market participants. Changes to interest rates therefore do not represent merely the central bank's response to changes in economic activity, as these should have already been incorporated into market prices.[26] By adding the information on immediate interest responses, it is possible to estimate which component of the change in interest rates not explained by the first step of the model can actually be attributed to the exogenous monetary policy impulse.

Results based on a proxy VAR model

ECB monetary policy impulses have a significant impact on the prices of crypto tokens …

After identifying the monetary policy impulses, their dynamic effects on the individual model variables can then be calculated, i.e. how the variables change over time solely due to monetary policy. A study conducted at the Bundesbank reaches the conclusion that the price of Bitcoin does indeed respond to Eurosystem monetary policy impulses to a statistically significant degree.[27] An unexpected reduction in the euro area's short-term interest rate level is estimated to lead to a persistent increase in the market value of Bitcoin as well as of other crypto tokens such as Ether and Litecoin. At first glance, the increase in prices is greater here than for shares or foreign currencies, which also see gains in value. If the much higher volatility of token prices is taken into account, however, this impression is relativised and the effects are of a roughly similar magnitude (see the box on pp. 79 ff.).

… but can only explain a small portion of price movements

This observation gives rise to the question of what overall share of the pronounced fluctuations in token prices can be attributed to monetary policy impulses from the Eurosystem. This question can also be answered using the econometric model, according to which the contribution made by monetary policy impulses is moderate: they are able to explain less than 10% of the variance in Bitcoin prices. Similar results are found for Ether and Litecoin. The much larger share of the changes in token prices must therefore be attributable to factors other than monetary policy in the euro area.[28] These might include changes in the general risk appetite of financial market participants,[29] but also factors specific to crypto tokens.[30] For example, the prices of tokens have often risen markedly in the past when large enterprises an-

25 This approach was largely developed by Stock and Watson (2012) and Mertens and Ravn (2013). It was first used to identify monetary policy shocks by Gertler and Karadi (2015).
26 If the central bank has information on future economic developments that is unknown to the market and therefore as yet unpriced, the market response could be attributed to an information shock. However, as outlined in the box on pp. 79 ff., such effects are controlled for in the current econometric analysis.
27 See Karau (2021).
28 US monetary policy also has a relatively low explanatory power in the model; see the box on pp. 79 ff.
29 Dyhrberg (2016), Bouri et al. (2017a, 2017b) and Kalyvas et al. (2020) analyse, for instance, the extent to which Bitcoin benefits from uncertainty in the international financial markets and can function as a hedging instrument.
30 Conlon and McGee (2020) establish that, prior to 2016, some of Bitcoin's price changes are associated with gambling transactions that can be conducted using the Bitcoin blockchain. Corbet et al. (2020) attribute some of the high volatility in the Bitcoin price to numerous cases of fraud and hacker attacks where bitcoins were illegally misappropriated. Gandal et al. (2018) analyse price manipulations in 2013 on the most significant crypto token trading platform at the time, Mt. Gox. According to Griffin and Shams (2020), the stablecoin Tether has been used in the past to manipulate the price of Bitcoin. In any case, crypto tokens are often associated with illegal activities. Foley et al. (2019) provide estimations of this using blockchain data and conclude that the illegal use of Bitcoin is a not insignificant driver of its market value.

The impact of monetary policy on crypto tokens in a VAR model

In a forthcoming Bundesbank discussion paper, the effects of monetary policy impulses on the market for crypto tokens are investigated using vector autoregressive (VAR) models.[1]

A VAR model consists of n variables that interact with one another over time. Rather than attempting to explain a specific variable using multiple others, each variable is regressed on lagged values of all of the variables included in the model. In mathematical terms, the estimated reduced form of the model is thus represented by the following system of equations

$$y_t = c + B_1 y_{t-1} + B_2 y_{t-2} + \dots + B_p y_{t-p} + u_t,$$

where y and c are respectively $(n \times 1)$ vectors of the endogenous model variables and constants, and p describes the number of lags taken into consideration. The $(n \times n)$ matrices B_i (where $i = 1,\dots,p$) contain the estimated regression coefficients, which indicate how the variables are dependent on one another over time. Finally, u_t is an $(n \times 1)$ vector of model residuals.

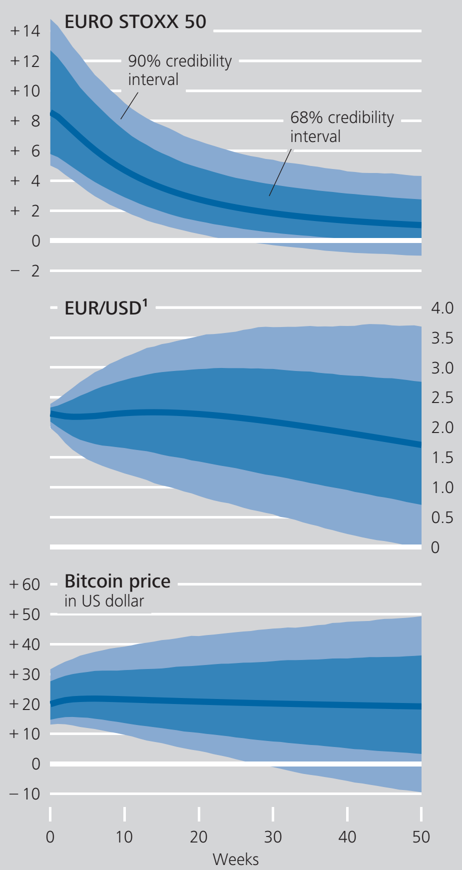
In total, six variables are included in the VAR model estimation:[2] the two-year euro area EONIA swap rate as a short-term interest rate,[3] the EURO STOXX 50 share price index, the euro/US dollar exchange rate, the VIX index (a measure of stock market volatility for the United States derived from options prices),[4] the VSTOXX (counterpart to the VIX for euro area shares), and, lastly, the price of Bitcoin in US dollars.[5] The reduced form of the model is estimated using Bayesian methods based on weekly data from the start of July 2013 to the end of June 2021.[6]

Following such a regression, the resulting model residuals are deviations of the observed data from the values predicted by the model. However, analysing the residuals

1 See Karau (2021).
2 With regard to the variables and the sample period, the model presented here is a slightly modified version of the models estimated in Karau (2021).
3 In the past, monetary policy impulses were often identified using money market interest rates with maturities shorter than two years. However, these have exhibited hardly any response to monetary policy decisions since March 2016, when the ECB Governing Council decided to lower the main refinancing rate to zero. For this reason, the literature has transitioned to analysing somewhat longer-term interest rates, which reflect monetary policy changes in the form of expectations regarding the future course of interest rates, for example (Gertler and Karadi (2015), Franz (2019), Jarociński and Karadi (2020)). Alternatively, a one-year interest rate could also be used here, or, instead of the EONIA rate, the yields on German government bonds. This changes the results of the estimations only slightly. In principle, shadow rates – i.e. counterfactual estimations of the money market rate that would have occurred without the zero lower bound – could also be used. However, these are associated with estimation uncertainty, which is not the case when using one-year or two-year market yields. Finally, the instrument variables described below are based on changes in two-year interest rates, and the use of equivalent yields in the VAR model improves instrument strength.
4 The VIX is often used to capture the uncertainty in the US and international financial markets that varies over time. It has been included here to control for such fluctuations econometrically.
5 All of the variables except for interest rates are included in the model in logarithmic form. There is hardly any change in the results if the Bitcoin price or other financial market variables are included in the system of equations in first differences.
6 Data on the market price of Bitcoin are available from as early as 2011. However, prior to mid-2013, the market was small and dominated by a single trading platform (Mt. Gox). In addition, there is evidence to suggest that, before mid-2013, the Bitcoin market was not efficient to the extent that daily returns were autocorrelated to a somewhat large degree, see Urquhart (2016). Nevertheless, if mid-2011 is chosen as the starting point for the analysis, there is hardly any change in the qualitative results; in quantitative terms, however, the effects are considerably smaller. The number of lags in the model is set as $p = 8$, which corresponds to two months. However, the exact choice of p has hardly any impact on the results.

Impulse response functions to an expansionary monetary policy shock*

%



* Reaction in the proxy VAR model to an expansionary monetary policy shock in the form of a reduction in the two-year interest rate by ten basis points. **1** Euro/US dollar exchange rate in direct quotation: a rise in the exchange rate corresponds to a depreciation of the euro.

Deutsche Bundesbank

alone is not sufficient to draw any conclusions regarding which factors are the determinants of each variable in the model. For example, if an unexpected (in model terms) downward deviation in the monetary policy rate – i.e. a negative residual – coincides with a subsequent unexpected upward deviation in financial market prices, this is not necessarily indicative of a causal relationship. Mathematically, the problem lies in the fact that the estimated residuals are correlated with one another. Intuitively, all possible determinants are drivers of both asset prices and monetary policy adjustments.

To be able to draw any conclusions regarding causality in the impact of monetary policy, we must isolate the component of the unexplained change in interest rates that does not represent a monetary policy response to other determinants, but instead constitutes its own exogenous impulse (structural shock). Over the course of time, the economic literature has developed a number of approaches for this purpose. These differ mainly in terms of which additional assumptions need to be made in order to identify individual structural shocks.[7] Proxy VAR models, for example, draw on information from outside the model itself in the form of instrumental variables.

A suitable instrument would be correlated with the shock to be identified, but not with other potential structural shocks. In most cases, the changes in short-term interest rates in narrow time windows around monetary policy decisions are used as instruments, as these are likely to be driven by monetary policy communication above all. However, in recent years, the economic literature has documented that the response of share prices, for instance, does not always seem to be in line with these changes in interest rates, which, according to theoretical considerations, were caused by a monetary policy shock. This phenomenon is usually explained in that the change

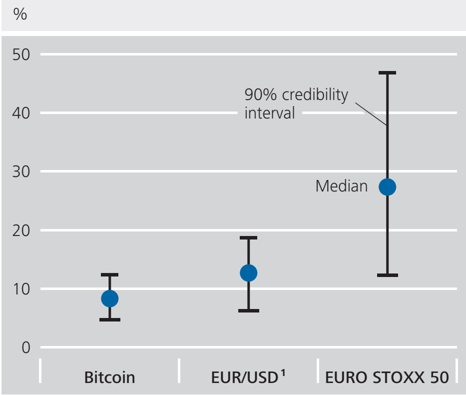
7 In the past, assumptions were often made regarding the time lags with which the individual variables respond to shocks. The individual shocks were then able to be identified by specifying a sequence of variables and subsequently decomposing the variance-covariance matrix of the residuals in triangular form. However, this approach is poorly suited to models that include financial market variables in particular. Another widely used approach for identifying shocks is based on sign restrictions imposed on the shocks. However, these must be derived from theoretical considerations, and it is often necessary to make a large number of assumptions in order to clearly differentiate individual shocks from one another. A detailed overview of procedures for identifying shocks can be found, for example, in Kilian and Lütkepohl (2017).

in interest rates by the central bank is sometimes interpreted as a signal of future economic developments – an information shock.[8] In order to filter out these non-monetary shocks, the instrument in the model described here takes account not only of the interest rate responses around monetary policy decisions, but also of the responses of share prices.[9]

Once the monetary policy shock is identified using the instrument, impulse response functions can be calculated. These show how a monetary policy impulse from the Eurosystem affects the individual variables in the system over time. In the chart on p. 80, the response of the price of Bitcoin in US dollars to a reduction in the two-year interest rate by ten basis points is compared with the responses of share prices and the exchange rate. In this context, the bands provide information on the statistical uncertainty of the estimation results. All three market prices rise to a statistically significant degree before the monetary policy effect diminishes again over time. Here, the percentage rise in the price of Bitcoin is far larger than the percentage rises in the exchange rate and the share price index. If, however, as shown in the chart on p. 73, account is taken of the high volatility of the Bitcoin price – which is four times higher than that of the share price index and eight times higher than that of the exchange rate – the relative effects of the monetary policy impulse are fairly similar in magnitude for all three asset prices.

To better assess the significance of monetary policy in each case, it is a good idea to decompose the forecast error variance. In this way, it is possible to estimate the extent to which, on average, the unexplained variations in the individual variables can be attributed to the identified monetary policy shock. Such an exercise reveals that only

Share of the forecast error variance explained by the monetary policy shock*



* Forecast error variance decomposition over a one-week horizon in the proxy VAR model. **1** Euro/US dollar exchange rate.
Deutsche Bundesbank

around 8% of the fluctuations in the Bitcoin price can be explained by monetary policy impulses from the Eurosystem. This is somewhat less than for the euro/US dollar exchange rate (around 12%) and considerably less than for the EURO STOXX 50 (around 28%), but also associated with less uncertainty.

The impression that monetary policy impulses only have a moderate impact on the market movements of crypto tokens does not change when the analysis is expanded. For instance, the prices of Litecoin and Ether respond similarly to the identified

8 For example, if interest rates were lowered, this could be interpreted as the central bank having a more pessimistic assessment of the economic outlook than it had before. As share prices are a reflection of expected corporate earnings, which respond sensitively to overall economic conditions, a reduction in interest rates could therefore lead to a drop in share prices. See Melosi (2017), Nakamura and Steinsson (2018), Cieslak and Schrimpf (2019), Kerssenfischer (2019), Jarociński and Karadi (2020) and Miranda-Agrippino and Ricco (2021). For an analysis of how such information shocks impact exchange rates, see Franz (2020).
9 These data are taken from the database in Altavilla et al. (2019). Using matrix rotation, an instrument series is created based on the short-term changes in interest rates and share prices. This then captures the adjustments resulting from a monetary policy shock where the signs of the responses of interest rates and share prices differ according to theory.

monetary policy shock.[10] In fact, in these cases, monetary policy explains an even slightly smaller component of the forecast error variance. Non-standard monetary policy likewise plays a similarly significant role in the valuation of crypto tokens. For example, in the analysis described above, the two-year interest rates could be replaced with ten-year interest rates; this would identify a shock that primarily captures the Eurosystem asset purchase programmes, which mainly affect longer-term interest rates. In this case, too, the monetary policy impulse explains a just slightly larger component of the variation in the Bitcoin price (and also the variation in the euro/US dollar exchange rate).[11]

Finally, the question could be raised of whether the prices of crypto tokens are driven not primarily by the monetary policy of the Eurosystem, but instead by that of the US Federal Reserve. This can also be investigated using the model described here by replacing each of the euro area variables with their US counterparts.[12] Interestingly, a model estimated in this way comes to an entirely different conclusion in qualitative terms. In this case, a monetary policy impulse from the Federal Reserve does not cause the prices of crypto tokens and other assets to respond in the same direction at all. For example, whilst an easing of monetary policy in the United States would lead to rises in the prices of US shares and foreign currency, the market value of Bitcoin would not also rise, but instead fall. While the reason behind this response cannot be given definitively, it may, however, be linked to the especially pronounced spillover effects from US monetary policy in conjunction with the technological and institutional particularities of Bitcoin.[13] Nevertheless, irrespective of the exact reason for the qualitative response, monetary policy shocks from the Federal Reserve can likewise explain just a relatively small component of the price fluctuations.

10 In the model, the Bitcoin price is then replaced by the price of Litecoin or Ether respectively, and the sample period is adjusted accordingly.
11 A shock identified in this manner is, however, not necessarily orthogonal to the previously observed shocks from more standard monetary policy at the short end of the yield curve. The components of the forecast error variance explained in each case therefore cannot simply be added together to obtain a picture of the overall impact of monetary policy.
12 The short-term responses of interest rates and share prices, which are necessary for the construction of the instrument, have been taken from the database of Cieslak and Schrimpf (2019) for the model for the United States.
13 Karau (2021) finds evidence that the rising demand for Bitcoin as a result of monetary policy tightening by the Federal Reserve is especially pronounced in emerging market economies. The literature shows that these countries are particularly affected by rises in US interest rates (see Miranda-Agrippino and Rey (2020) and Degasperi et al. (2020)), for example due to shifts in capital by international investors and globally active banks (see Bruno and Shin (2015) and Kalemli-Özcan (2019)). Accordingly, if the economic and financial conditions in those countries deteriorate, this could boost demand for assets like crypto tokens, which, unlike the normal financial system, are subject to hardly any regulation in those jurisdictions and can be easily transferred across national borders.

nounced that they would accept Bitcoin as a means of payment for their products or that they intended to invest in Bitcoin themselves. There is also evidence to suggest that market prices often respond sensitively to announcements made by supervisory authorities indicating regulatory changes for tokens.[31]

Similar results when analysing effects of non-standard monetary policy

The assessment that the Eurosystem's monetary policy cannot sufficiently explain token price developments does not change when looking at non-standard measures either. For example, Eurosystem central banks purchase large amounts of bonds as part of various asset purchase programmes and thereby exert pressure on long-term interest rates.[32] It is sometimes argued that it is these non-standard measures in particular that are partly responsible for the high valuation of various assets.[33] The effects of this policy can be investigated using the approach described here by including the yields of long-term government bonds in the VAR model. Changes to these long-term interest rates within narrow time windows around monetary policy announcements are thus used as instrumental variables in order to identify non-standard monetary policy impulses. The results provide a similar picture to the one before: a decline in yields on ten-year German government bonds attributable to monetary policy causes a statistically significant increase in the Bitcoin price; the quantitative effect of this is small, however, and it can only explain a moderate portion of the overall fluctuations.

Conclusion

Monetary policy impulses have a significant effect on the prices of many assets. While their impact on bonds, shares or exchange rates has been studied extensively on both a theoretical and empirical level, their relationship with crypto tokens such as Bitcoin is less obvious at first. Nevertheless, the higher valuation levels of individual tokens are sometimes perceived as excessive speculation, which has occasionally been blamed partly on the more accommodative monetary policies of major central banks.

Should the prices of Bitcoin and other similarly designed tokens primarily be driven by more accommodative monetary policy or reflect, for instance, the fears of supposed inflationary pressures, they might respond sensitively to monetary policy impulses. Indeed, the already pronounced volatility of token prices does tend to be higher around monetary policy announcements made by the ECB's Governing Council than at other times. Likewise, the prices of tokens correlate somewhat more strongly with those of shares and exchange rates in immediate response to the Eurosystem's monetary policy communication. That said, the relative significance of monetary policy in the euro area does not appear to be greater at first glance, but instead it generally seems to be lower and less statistically significant than for conventional assets.

A similar picture emerges following a systematic analysis over longer periods. When econometric methods are used to identify Eurosystem monetary policy impulses, there is evidence to suggest that monetary policy has a significant effect on the price of Bitcoin, for example. However, the Eurosystem's monetary policy can only explain a relatively minor part of the overall evolution in Bitcoin's value, and most of this development has to be attributed to other determinants. Based on historical data, it thus cannot be deduced that, on account of their characteristics, the prices of crypto tokens are driven by monetary policy to any exceptional extent.

31 See Auer and Claessens (2018).
32 Deutsche Bundesbank (2016) provides a detailed overview of the Eurosystem's purchase programmes. Their impact on the euro's exchange rate is analysed in Deutsche Bundesbank (2017a).
33 See, for example, De Haan and van den End (2018).

List of references

Aloosh, A. and J. Li (2021), Direct Evidence of Bitcoin Wash Trading, Working Paper, https://ssrn.com/abstract=3362153

Altavilla, C., L. Brugnolini, R. S. Gürkaynak, R. Motto and G. Ragusa (2019), Measuring Euro Area Monetary Policy, Journal of Monetary Economics, 108, pp. 162-179.

Ankenbrand, T. and D. Bieri (2018), Assessment of cryptocurrencies as an asset class by their characteristics, Investment Management and Financial Innovations, Vol. 15, pp. 169-181.

Arner, D., R. Auer and J. Frost (2020), Stablecoins: risks, potential and regulation, BIS Working Paper No 905.

Auer, R. (2019), Beyond the doomsday economics of proof-of-work in cryptocurrencies, CEPR Discussion Paper No 13506.

Auer, R. and R. Böhme (2020), An introduction to public-private key cryptography in digital tokens, BIS Quarterly Review, March 2020, p. 73.

Auer, R. and S. Claessens (2018), Regulating cryptocurrencies: assessing market reactions, BIS Quarterly Review, September 2018, pp. 51-65.

Bernanke, B. and K. Kuttner (2005), What Explains the Stock Market's Reaction to Federal Reserve Policy?, Journal of Finance, Vol. 60, No 3, pp. 1221-1257.

Bloomberg (2021), Pandemic-Era Central Banking Is Creating Bubbles Everywhere, https://www.bloomberg.com/news/features/2021-01-24/central-banks-are-creating-bubbles-everywhere-in-the-pandemic

Borio, C. and H. Zhu (2012), Capital Regulation, Risk-Taking and Monetary Policy: A Missing Link in the Transmission Mechanism?, Journal of Financial Stability, Vol. 8, No 4, pp. 236-251.

Bouri, E., R. Gupta, A. Tiwari and D. Roubaud (2017a), Does Bitcoin hedge global uncertainty? Evidence from wavelet-based quantile-in-quantile regressions, Finance Research Letters, Vol. 23, pp. 87-95.

Bouri, E., P. Molnár, G. Azzi, D. Roubaud and L. Hagfors (2017b), On the hedge and safe haven properties of Bitcoin: Is it really more than a diversifier?, Finance Research Letters, Vol. 20, pp. 192-198.

Bruno, V. and H. Shin (2015), Capital flows and the risk-taking channel of monetary policy, Journal of Monetary Economics, Vol. 71(C), pp. 119-132.

Budish, E. (2018), The Economic Limits of Bitcoin and the Blockchain, NBER Working Paper No 24717.

Buterin, V. (2013), A Next-Generation Smart Contract and Decentralized Application Platform, https://ethereum.org/en/whitepaper/

Chainalysis (2021), Cryptocurrency Ecosystem Comparison: Bitcoin vs. Ethereum vs. Stablecoins, https://blog.chainalysis.com/reports/cryptocurrency-ecosystem-bitcoin-ethereum-stablecoins

Choi, K., A. Lehar and R. Stauffer (2020), Bitcoin Microstructure and the Kimchi Premium, Mimeo, https://ssrn.com/abstract=3189051

Cieslak, A. and A. Schrimpf (2019), Non-Monetary News in Central Bank Communication, Journal of International Economics, Vol. 118, pp. 293-315.

Cong, L., X. Li, K. Tang and Y. Yang (2021), Crypto Wash Trading, Mimeo.

Conlon, T. and R. McGee (2020), Betting on Bitcoin: Does gambling volume on the blockchain explain Bitcoin price changes?, Economics Letters, Vol. 191, 108727.

Corbet, S., D. Cumming, B. Lucey, M. Peat and S. Vigne (2020), The destabilising effects of cryptocurrency cybercriminality, Economics Letters, Vol. 191, 108741.

Corbet, S., B. Lucey, A. Urquhart and l. Yarovaya (2019), Cryptocurrencies as a financial asset: A systematic analysis, International Review of Financial Analysis, Vol. 62, pp. 182-199.

d'Avernas, A., T. Bourany and Q. Vandeweyer (2021), Are Stablecoins Stable?, Mimeo.

De Haan, L. and J. W. van den End (2018), The signalling content of asset prices for inflation: Implications for quantitative easing, Economic Systems, Vol. 42, pp. 45-63.

De Vries, A. (2018), Bitcoin's growing energy problem, Joule, Vol. 2, No 5, pp. 801-805.

Dedola, L., G. Georgiadis, J. Gräb and A. Mehl (2021), Does a big bazooka matter? Quantitative easing policies and exchange rates, Journal of Monetary Economics, Vol. 117(C), pp. 489-506.

Degasperi, R., S. Hong and G. Ricco (2020), The Global Transmission of U. S. Monetary Policy, CEPR Discussion Paper No 14533.

Deutsche Bundesbank (2021), Crypto tokens and decentralised financial applications, Monthly Report, July 2021, pp. 31-48.

Deutsche Bundesbank (2020), The impact of monetary policy on the euro's exchange rate, Monthly Report, September 2020, pp. 19-51.

Deutsche Bundesbank (2019), Crypto tokens in payments and securities settlement, Monthly Report, July 2019, pp. 39-59.

Deutsche Bundesbank (2017a), The Eurosystem's bond purchases and the exchange rate of the euro, Monthly Report, January 2017, pp. 13-39.

Deutsche Bundesbank (2017b), Distributed ledger technologies in payments and securities settlement: potential and risks, Monthly Report, September 2017, pp. 35-49.

Deutsche Bundesbank (2016a), Indications of portfolio shifts into higher-yielding assets in Germany, Monthly Report, May 2016, pp. 34-37.

Deutsche Bundesbank (2016b), The macroeconomic impact of quantitative easing in the euro area, Monthly Report, June 2016, pp. 29-53.

Deutsche Bundesbank (2005), Exchange rates and interest rate differentials: recent developments since the introduction of the euro, Monthly Report, July 2005, pp. 27-42.

Di Maggio, M. and M. Kacperczyk (2016), The Unintended Consequences of the Zero Lower Bound Policy, Journal of Financial Economics, Vol. 123, No 1, pp. 59-80.

Divakaruni, A. and P. Zimmerman (2020), Ride the Lightning: Turning Bitcoin into Money, https://ssrn.com/abstract=3514125

Dyhrberg, A. (2016), Hedging capabilities of bitcoin. Is it the virtual gold?, Finance Research Letters, Vol. 16, pp. 139-144.

Easley, D., M. O'Hara and S. Basu (2019), From mining to markets: The evolution of bitcoin transaction fees, Journal of Financial Economics, Vol. 134, No 1, pp. 91-109.

Eyal, I. and E. Sirer (2014), Majority is not enough: Bitcoin mining is vulnerable, in: International conference on financial cryptography and data security, Springer, pp. 436-454.

Federal Office for Information Security (2019), Towards Secure Blockchains – Concepts, Requirements, Assessments, https://www.bsi.bund.de/SharedDocs/Downloads/EN/BSI/Crypto/Secure_Blockchain.pdf?__blob=publicationFile&v=3

Foley, S., J. Karlsen and T. Putninš (2019), Sex, Drugs, and Bitcoin: How Much Illegal Activity Is Financed through Cryptocurrencies?, Review of Financial Studies, Vol. 32, No 5, pp. 1798-1853.

Franz, T. (2020), Central bank information shocks and exchange rates, Deutsche Bundesbank Discussion Paper No 13/2020, March 2020.

Gandal, N. and H. Halaburda (2016), Can we predict the winner in a market with network effects? Competition in cryptocurrency market, Games, Vol. 7, No 3, pp. 1-21.

Gandal, N., J. Hamrick, T. Moore and T. Oberman (2018), Price manipulation in the Bitcoin ecosystem, Journal of Monetary Economics, Vol. 95, pp. 86-96.

Gans, J. and N. Gandal (2019), More (or Less) Economic Limits of the Blockchain, NBER Working Paper No 26534.

Garratt, R. and R. Hayes (2014), Bitcoin: How Likely Is a 51 Percent Attack?, Liberty Street Economics Blog, Federal Reserve Bank of New York, https://libertystreeteconomics.newyorkfed.org/2014/11/bitcoin-how-likely-is-a-51-percent-attack/

Gertler, M. and P. Karadi (2015), Monetary Policy Surprises, Credit Costs, and Economic Activity, American Economic Journal: Macroeconomics, Vol. 7, No 1, pp. 44-76

Gilchrist, S., V. Yue and E. Zakrajšek (2019), U. S. Monetary Policy and International Bond Markets, Journal of Money, Credit and Banking, Vol. 51, No 1, pp. 127-161.

Gorton, G. and J. Zhang (2021), Taming Wildcat Stablecoins, Working Paper, https://ssrn.com/abstract=3888752

Griffin, J. and A. Shams (2020), Is Bitcoin Really Untethered?, Journal of Finance, Vol. 75, No 4, pp. 1913-1964.

Gürkaynak, R., A. Kara, B. Kisacikoglu and S. Lee (2021), Monetary Policy Surprises and Exchange Rate Behavior, Journal of International Economics, Vol. 130(C), 103443.

Gürkaynak, R., B. Sack and E. Swanson (2005), Do Actions Speak Louder than Words? The Response of Asset Prices to Monetary Policy Actions and Statements, International Journal of Central Banking, Vol. 1, No 1, pp. 55-93.

Halaburda, H., G. Haeringer, J. Gans and N. Gandal (2020), The Microeconomics of Cryptocurrencies, NBER Working Paper No 27477.

Harvey, C., H. Zhu and L. Yan (2016), … and the Cross-Section of Expected Returns, The Review of Financial Studies, Vol. 29, pp. 5-68.

Huberman, G., J. Leshno and C. Moallemi (2020), Monopoly without a Monopolist: An Economic Analysis of the Bitcoin Payment System, Columbia Business School Research Paper No 17-92, https://ssrn.com/abstract=3025604

Jarociński, M. and P. Karadi (2020), Deconstructing Monetary Policy Surprises – The Role of Information Shocks, American Economic Journal: Macroeconomics, Vol. 12, No 2, pp. 1-43.

Jiménez, G., S. Ongena, J.-L. Peydró and J. Saurina (2015), Hazardous Times for Monetary Policy: What Do Twenty-Three Million Bank Loans Say About the Effects of Monetary Policy on Credit Risk-Taking?, Econometrica, Vol. 82, No 2, pp. 463-505.

Kalemli-Özcan, S. (2019), U.S. Monetary Policy and International Risk Spillovers, NBER Working Paper No 26297.

Kalyvas A., P. Papakyriakou, A. Sakkas and A. Urquhart (2020), What drives Bitcoin's price crash risk?, Economics Letters, Vol. 191, 108777.

Karau, S. (2021), Monetary Policy and Bitcoin, Deutsche Bundesbank Discussion Paper, forthcoming.

Kerssenfischer, M. (2019), Information Effects of Euro Area Monetary Policy: New Evidence from High-Frequency Futures Data, Deutsche Bundesbank Discussion Paper, No 07/2019, February 2019.

Kilian, L. and H. Lütkepohl (2017), Structural Vector Autoregressive Analysis, Cambridge University Press.

Klages-Mundt, A., D. Harz, L. Gudgeon, J.-Y. Liu and A. Minca (2020), Stablecoins 2.0: Economic foundations and risk-based models, in: Proceedings of the 2nd ACM Conference on Advances in Financial Technologies, pp. 59-79.

Kroeger, A. and A. Sarkar (2016), Is Bitcoin Really Frictionless?, Liberty Street Economics Blog, Federal Reserve Bank of New York, https://libertystreeteconomics.newyorkfed.org/2016/03/is-bitcoin-really-frictionless.html

Kuttner, K. (2001), Monetary policy surprises and interest rates: Evidence from the Fed funds futures market, Journal of Monetary Economics, Vol. 47, pp. 523-544.

Li, Y. and S. Mayer (2020), Managing Stablecoins: Optimal Strategies, Regulation, and Transaction Data as Productive Capital, Ohio State University Working Paper No 2020-30, Charles A. Dice Center for Research in Financial Economics.

Libra Association (2019), An Introduction to Libra, https://sls.gmu.edu/pfrt/wp-content/uploads/sites/54/2020/02/LibraWhitePaper_en_US-Rev0723.pdf

Liu, Y. and A. Tsyvinski (2018), Risks and Returns of Cryptocurrency, NBER Working Paper No 24877.

Lyons, R. and G. Viswanath-Natraj (2020), What Keeps Stablecoins Stable?, NBER Working Paper No 27136.

Ma, J., J. Gans and R. Tourky (2018), Market Structure in Bitcoin Mining, NBER Working Paper No 24242.

Makarov, I. and A. Schoar (2020), Trading and arbitrage in cryptocurrency markets, Journal of Financial Economics, Vol. 135, No 2, pp. 293-319.

Melosi, L. (2017), Signalling Effects of Monetary Policy, Review of Economic Studies, Vol. 84, pp. 853-884.

Mertens, K. and M. Ravn (2013), The Dynamic Effects of Personal and Corporate Income Tax Changes in the United States, American Economic Review, Vol. 103, No 4, pp. 1212-1247.

Miranda-Agrippino, S. and H. Rey (2020), U. S. Monetary Policy and the Global Financial Cycle, Review of Economic Studies, Vol. 87, No 6, pp. 2754-2776.

Miranda-Agrippino, S. and G. Ricco (2021), The Transmission of Monetary Policy Shocks, American Economic Journal: Macroeconomics, Vol. 13, No 3, pp. 74-107.

Nakamoto, S. (2009), Bitcoin open source implementation of P2P currency, forum post on the website of the P2P Foundation, http://p2pfoundation.ning.com/forum/topics/bitcoin-open-source

Nakamoto, S. (2008), Bitcoin: A Peer-to-Peer Electronic Cash System, https://bitcoin.org/bitcoin.pdf

Nakamura, E. and J. Steinsson (2018), High-Frequency Identification of Monetary Non-Neutrality: The Information Effect, The Quarterly Journal of Economics, Vol. 133, No 3, pp. 1283-1330.

Prat, J. and B. Walter (2021), An Equilibrium Model of the Market for Bitcoin Mining, Journal of Political Economy, Vol. 129, No 8.

Rajan, R. (2005), Has Financial Development Made the World Riskier?, Jackson Hole 2005 Symposium Proceedings, Federal Reserve Bank of Kansas City.

Soiman, F., M. Mourey, J.-G. Dumas and S. Jimenez-Garces (2021), The forking effect, Mimeo.

Stock, J. and M. Watson (2012), Disentangling the Channels of the 2007-2009 Recessions, NBER Working Paper No 18094.

Urquhart, A. (2016), The inefficiency of Bitcoin, Economics Letters, Vol. 148, pp. 80-82.

Zettelmeyer, J. (2004), The Impact of Monetary Policy on the Exchange Rate: Evidence from three small Open Economies, Journal of Monetary Economics, Vol. 51, pp. 635-652.