Chapter 2

c0010 # A panorama of applications of blockchain technology to energy

Matthew Gough[a,b], Rui Castro[c], Sérgio F. Santos[b], Miadreza Shafie-khah[d] and João P.S. Catalão[e]

[a]*Superior Technical Institute, Lisbon, Portugal,* [b]*INESC TEC, Porto, Portugal,* [c]*INESC-ID/IST, University of Lisbon, Lisbon, Portugal,* [d]*School of Technology and Innovations, University of Vaasa, Vaasa, Finland,* [e]*Faculty of Engineering of the University of Porto and INESC TEC, Porto, Portugal*

s0010 ## 1. Introduction

p0010 The blockchain technology has the potential to have a significant impact in many sectors in the modern economy, including the energy sector. Numerous use cases for blockchain in the energy sector have been proposed. These include wholesale and retail energy trading, environmental attribute management, aiding demand response programs, and enabling new sources of financing for energy projects.

p0015 The blockchain technology has been likened to the Internet in its potential to revolutionize the economy. Other sources say that it is nothing more than a passing fad. This chapter provides evidence on both counts. The potential impact of the blockchain technology is presented, and it is shown that there are cases where the blockchain technology could have significant impacts on the energy sector. That being said, there are a number of challenges that the technology also needs to overcome before it is adopted in a widespread manner.

p0020 This chapter is composed of the following sections: an introduction where the context surrounding both the blockchain and the current energy sector is discussed. Following this the blockchain in introduced including the technological background. Then a section of current and past blockchain projects is presented along with a table detailing nearly 150 companies who are active in the energy and blockchain ecosystem. A section of the various limitation of blockchain is then presented followed by a section detailing regulatory aspects relating to blockchain in the energy sector. Following this the major contribution of this work is presented as the various applications of blockchain in energy are detailed.

Blockchain-based Smart Grids. https://doi.org/10.1016/B978-0-12-817862-1.00002-6

s0015 1.1 Context

p0025 The context surrounding blockchain is extremely important in discussing where the technology comes from and where it may be heading in the future. A group of underlying technologies has coalesced to form the blockchain technology, and there are a wide variety of factors that brought these technologies together. This section will discuss the context surrounding blockchain and give the reader a better idea of where the technology originates from and why it has been touted as being a game-changer in the energy sector.

p0030 Even before blockchain becomes a hot button issue, the energy sector was beginning to undergo a significant transition. This is shown from a survey conducted in 2013 where 94% of the senior power and utility executives expected either a complete transformation or important changes in the power utility business model by the year 2030 [1]. The impact of the blockchain technology on the energy sector could be very significant as approximately 20% of respondents to a survey conducted by the German Energy Agency believe that the technology will be a "game-changer" for the sector [2]. The context surrounding the energy system is one that can be characterized by the three D's of decarbonization, decentralization, and digitalization, and especially in Europe, there is an overarching goal to empower consumers and put them at the heart of the future energy system [3]. Blockchain can assist in both the decentralization and digitization aspects of the ongoing energy transition.

p0035 The existing electricity system is characterized by consumers with little to no control over their electricity use and a paradigm of load-following power plants and very little information available concerning the operating conditions of the system [4]. There is a confluence of factors that are changing how the existing electricity system operates. Chief among these factors is the rapid growth of distributed energy resources (DERs), and this leads to increased customer choice and participation in the electricity market. This paradigm shift has been noted by existing firms, and significant amounts of capital are being spent to upgrade the existing electric system. Estimates suggest that $47 billion was spent in 2016 in upgrades to modernize the electricity system [4]. Despite this significant influx of capital, the current power system still largely functions the way it did in the 20th century. This could be down to the fact that major electricity utilities are normally very risk averse and have to deal with regulatory oversight that could stymie progress [4].

p0040 Blockchain helps by reducing two types of transaction costs. The first is the verification of the qualities of a transaction, and the second is the costs of operating a marketplace, which blockchain lowers by removing the need for a trusted third party [5]. By lowering these two costs, blockchain can help create more fluid marketplaces that allow for increased competition, reduced barriers to entry, and lower risks associated with privacy and censorship concerns [5]. Blockchain allows for the transfer of value between two untrusting peers without the requirement of having a trusted third party to verify the transaction [5].

p0045 Trust in institutions and on the Internet has been eroded, and this has led to many people questioning the notion of centralized systems with trusted partners [6]. In the past a trusted third party was needed to verify the transaction between two parties. This verification process increased the cost and time taken to complete the transaction, but it was an acceptable trade-off as the third part helped mitigate the risks associated with the information asymmetry and moral hazard problems [5]. The core innovation behind the blockchain technology is the fact that it stores multiple copies of the transaction history and that the copies of the transaction history are connected through a validation mechanism that is secure [7]. Catalini and Gans [5] suggest that the blockchain has allowed for costless verification of transactions. But it may be more correct to say that the requirement of being trustworthy has shifted from the intermediary to the builders of the blockchain code and the chosen consensus mechanism. Therefore blockchain doesn't remove the need for trust; it allows the creation of more trustful relationships [8].

p0050 The blockchain technology is expected to have a profound impact on the way that individuals transact among themselves with an oft-cited comparison and has the transformative effect on Internet communication brought about by the introduction of the TCP/IP protocols [5]. Blockchain may help unleash the so-called Internet of Things (IoT). As the number of IoT devices grows worldwide, they will require a secure protocol on which to communicate and transact with each other, and the blockchain may be able to play this pivotal role [5]. Added to this is the fact that the blockchain can transfer details concerning property rights and that these decentralized networks are more resistant to one agent having significant market power. Lowering the barriers to entry in these networks will allow new innovative solutions to be developed, and this will reduce the market power of the existing incumbents. Work carried out by the Research Institute of the Finnish Economy shows that the blockchain technology could play a key role as the interoperability layer in a world with a large penetration of IoT devices [9]. There has been an explosion of interest in blockchain in the past few years. There are numerous conferences and events that have emerged to deal with the blockchain technology and more specifically to investigate the blockchain's potential impact on the energy sector. There has been 24 blockchain-themed conferences in the last 6 months of 2018 [10]. The underlying technology behind the blockchain (cryptography, peer-to-peer networks, and data storage) has all existed for a significant amount of time. What the blockchain does that is so powerful is to combine these three areas of research with various economic incentives, and this allows for the growth of decentralized markets [11].

p0055 The use of decentralized systems may also affect the role of the individual in society. For example, in the energy sector, individuals have often had to be passive consumers in which they bought from a centralized source, such as an electric utility. In decentralized and peer-to-peer-based societies, there is scope for the consumer to take on a much more proactive role, and they could become producers of a product as well [12]. The concept of a decentralized electricity system has been spoken about for a considerable time, and the rise of energy

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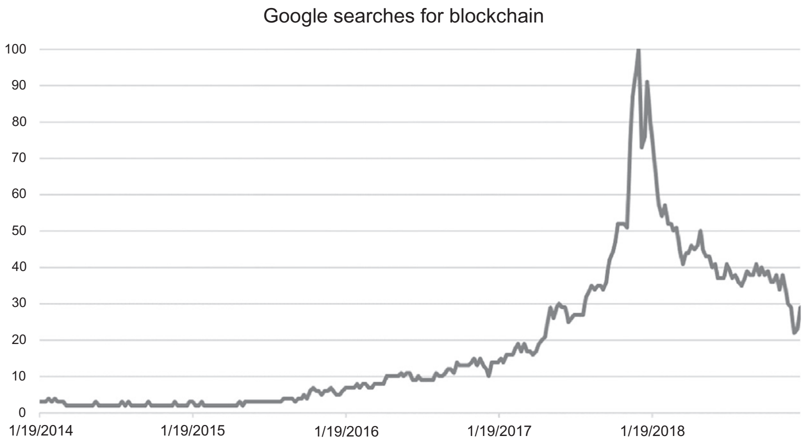


f0010 **FIG. 1** The considerable rise and decrease in the number of searches for "blockchain." *(Authors' own using data from Google Trends.)*

storage devices and electric mobility, as well as new control systems for demand response, has made the concept of a decentralized grid more tractable.

p0060 While there is significant hype surrounding blockchain at the moment, it is thought that blockchain will be truly successful when people use it seamlessly as part of their everyday lives without realizing that they are using blockchain much like the general public uses the Internet today without having to think about the various technologies and protocols that underpin the Internet.

p0065 The blockchain technology has received significant attention in the past few years. This can be shown through the Google Trends depicted in Fig. 1. This image shows the popularity of the search topic "blockchain" over the past 5 years. It is a proportional figure where the score of 100 means that this was the peak value of searches for the term and a score of 50 represents a total number of daily searches equal to half of the maximum recorded.

p0070 Again, parallels with the growth of the Internet can be made regarding how to ensure future growth of the blockchain technology. The Internet experienced enormous growth when it was user-friendly enough and understandable by the general population. Also, it was predicted that the Internet will usher in a new era of decentralization, but instead, it has become very centralized, and it could be argued that it is undemocratic [13].

p0075 In the context of the modern economy with its drive toward the knowledge economy that focuses on knowledge-led growth rather than the traditional means of production, information is playing a key role. Information has become a crucial resource in the modern world [8]. Whoever controls the information can wield significant market power, and the blockchain may be able to democratize information and reduce the market power of existing incumbents that have based their business on the centralized storage and use of information.

s0020 1.2 Definitions

s0025 *1.2.1 Blockchain*

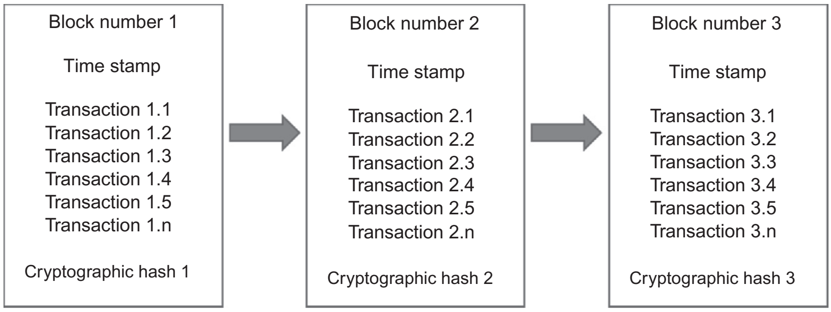
p0080 There exist numerous definitions for the blockchain, but the general definition of the blockchain is given by Bashir [14]:

dq0010 *Blockchain at its core is a peer-to-peer distributed ledger that is cryptographically secure, append-only, immutable (extremely hard to change), and updateable only via consensus or agreement among peers. From a business point of view, a blockchain can be defined as a platform whereby peers can exchange values using transactions without the need for a centrally trusted arbitrator. A block is simply a selection of transactions bundled together in order to organize them logically. It is made up of transactions and its size is variable depending on the type and design of the blockchain in use. A reference to a previous block is also included in the block unless it's a genesis block. A genesis block is the first block in the blockchain that was hardcoded at the time the blockchain was started.*

Another definition is given by Andoni et al. [15]:

dq0015 *Blockchains are shared and distributed data structures or ledgers that can securely store digital transactions without using a central point of authority. The data structure is, in other words, a ledger that may contain digital transactions, data records and executables. Instead of managing the ledger by a single trusted center, each individual network member holds a copy of the records' chain and reach an agreement on the valid state of the ledger with consensus. The exact methodology of how consensus is reached is an ongoing area of research and might differ to suit a wide range of application domains. New transactions are linked to previous transactions by cryptography which makes blockchain networks resilient and secure. Every network user can check for themselves if transactions are valid, which provides transparency and trustable, tamper-proof records.*

These two definitions touch on a number of concepts that may be unfamiliar. These concepts are distributed ledger, append-only, immutable, and consensus. These concepts are defined as follows: A distributed ledger is a ledger that is distributed among its participants and spread across multiple sites or organizations and does not reside with a central authority. Append-only means information can only be added, not removed in contrast to read-write databases where information may be removed. Immutable refers to the property of being tamper proof, and while a blockchain can be called immutable, it is technically possible to change the records stored within a blockchain system, but it is extremely computationally taxing, and thus for practical purposes the blockchain system is classified as immutable [14]. Consensus is the method that the various nodes in the blockchain system reach agreement on the various blocks of transactions before being incorporated into the existing blockchain [7]. There are numerous consensus mechanisms that can be used, and these will be described in the coming sections.



f0015 **FIG. 2** Typical blockchain system. *(Author modified from J.A.F. Castellanos, D. Coll-Mayor, J.A. Notholt, Cryptocurrency as guarantees of origin: simulating a green certificate market with the Ethereum Blockchain, in: 2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE), in: Presented at the 2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE), 2017, pp. 367–372. https://doi.org/10.1109/SEGE.2017.8052827.)*

p0090 Fig. 2 shows the general layout of a blockchain structure after Castellanos et al. [16]. This figure shows a number of blocks each containing a number of transactions. Each block has a sequential number and a time stamp to allow for easy auditing of the blockchain history. Each block also has a unique cryptographic hash that will change should any validated transaction be modified. As each block also makes use of the previous block's cryptographic hash, should any transaction change in any of the preceding blocks, it will change the entire blockchain, and therefore the modification can be easily identified and rectified.

p0095 Once a transaction has been requested by a node, it is then broadcast to the rest of the network, which then validates the transaction using the network's chosen consensus mechanism. Once the validation stage is completed, the transaction is then added to a block, and then the block containing a number of validated transactions is added to the existing blockchain.

p0100 These various characteristics of blockchain allow digital information to have a value assigned to them. As Joe Ito, the director of MIT's Media Lab, said, "The blockchain makes information look like a thing. It creates the scarcity that you couldn't do on the internet" [17]. This set of technologies that make up blockchain brings together a group of individuals who act in their own self-interest, but together, this group can create an immutable, trustworthy, decentralized system [8].

p0105 By prohibiting double spending of the currency, Bitcoin allowed for the creation of a digital asset [8]. In the era before Bitcoin (and the underlying blockchain technology), digital information could easily be replicated and shared (e.g., images and songs). However, blockchain can include an immutable and time-stamped signature of the creator or the original owner, and the spread of that piece of information can now be tracked. It can be said that blockchain (first through the Bitcoin protocol) introduced the concept of digital scarcity.

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p0110 There are a number of different blockchain types, but the two largest and well known (Bitcoin and Ethereum) will be discussed in the coming sections. They were chosen as Bitcoin is the largest and oldest blockchain system and Ethereum is interesting for the energy sector as it allows applications to be scripted in the blockchain using the Solidity programming language. Ripple is another interesting blockchain application, but as it focuses more on the financial sector, it is excluded from this chapter.

s0030 *1.2.2 Bitcoin*

p0115 Bitcoin was introduced nearly 10 years ago in a paper authored by Satoshi Nakamoto (a pseudonym) [18]. Since its introduction, it has become the largest cryptocurrency with an approximate market capitalization of $70 billion as of January 2019. Bitcoin is a collection of peer-to-peer networks, protocols, and software that allow for the creation and usage of bitcoin, a digital currency. Bitcoin can be defined in several ways as it acts as a protocol, a digital currency, and a platform [14]. This section will follow the existing protocol of using Bitcoin, with a capital B when discussing the protocol and bitcoin, with a lowercase b, when discussing the digital currency. Even though Bitcoin is the first and most successful implementation of the blockchain technology, the word "blockchain" never appears in the original paper presented by Satoshi Nakamoto.

p0120 Bitcoin's core protocols have so far proven to be very resilient to malicious actors or hacking. Despite being a decentralized system with no central dedicated cybersecurity tools and having a potential $70 billion (as of January 2019) in assets, there have been no successful hacking attempts [8]. However, this does not mean that Bitcoin is inherently safe; there have been instances of hackers gaining access to individual's wallets (where the amount of bitcoin is stored) or obtaining access to the digital currency exchanges where customers can buy and trade cryptocurrency for fiat currency, but this is a software issue relating to the security of the wallet software or the security protocols of the cryptocurrency exchanges and not the inherent Bitcoin protocol. There have also been cases of hackers manipulating the blockchain of smaller cryptocurrencies, such as Bitcoin Gold and Ethereum Classic, but a discussion of that falls outside the scope of this chapter.

p0125 Satoshi Nakamoto was not the first to design and implement a digital currency, but what sets Bitcoin apart from the previous attempts is the way that it uses a collection of technologies to make the issue of double spending of the currency extremely difficult. To be clear, double spending is possible on the Bitcoin system, but it is extremely expensive, and this high cost has so far prohibited any individual from successfully double spending a bitcoin. To double spend a bitcoin, an individual would need to control 51% of the computing power of the Bitcoin network to ensure that their version of the Bitcoin blockchain was accepted as the "true" version even if this version of the blockchain contained fraudulent transactions. The costs of such a 51% attack on the Bitcoin blockchain is estimated to cost over $7 billion dollars as of the middle of January 2019 [19].

p0130 The manner in which the nodes of a distributed system agree on the correct version of the ledger is known as consensus [14]. Once consensus has been reached, the block of transactions is permanently added to the existing blockchain. Numerous methods exist for reaching consensus, and the exact manner in which consensus is reached can differ depending on the type and nature of the underlying blockchain.

p0135 The European Commission recognizes the major contribution of Bitcoin to be the ability to "establish trust between two mutually unknown and unrelated parties to such extent that sensitive and secure transactions can be performed with full confidence over an open environment, such as the Internet" [20].

s0035 *1.2.3 Ethereum*

p0140 After Bitcoin the most well-known blockchain is Ethereum. Ethereum also has the second highest market capitalization after Bitcoin with a market capitalization of approximately $16 billion as of January 2019. Ethereum was proposed in late 2013 by then 19-year-old Vitalik Buterin, and he and a group of core developers maintain and upgrade the network.

p0145 What sets Ethereum apart from Bitcoin is its built-in programming language that allows it to develop and deploy distributed applications including smart contracts [21]. This allows developers to create applications that run on top of the blockchain and make use of its characteristics. The programming language used within the Ethereum environment is Solidity, and it is a Turing-complete language [8].

p0150 To carry out a transaction on the Ethereum blockchain, a user must pay a transaction fee, which is termed "gas." This transaction cost covers the cost of computation required to carry out the instruction, so the more detailed and complicated the instruction, the higher the gas fee [14].

p0155 A further evolution of the blockchain system into what is termed Blockchain 3.0 saw the arrival of decentralized applications (DApps) or decentralized autonomous organizations (DAOs). DAOs are defined solely by a collection of smart contracts and allow for operation in a business like environments without the need for human intervention [11]. While this automation of business activities may sound appealing, it could be a very worrisome property if taken to its full capacity. The full automation of the DAO will mean that, once it has been initiated, no one can alter its underlying business logic. Traditional entities adapt over time to better suit their changing environments [21]. A DAO will not be able to do such a thing, and if there is an error in its programming, no one can correct it.

s0040 *1.2.4 Smart contracts*

p0160 A key characteristic of the current blockchain ecosystem is the smart contract. While these contracts have emerged as a major defining characteristic of the

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so-called Blockchain 2.0, the concept of smart contracts has existed for longer than the blockchain concept.

p0165 Nick Szabo first defined smart contracts in 1996 as those type of contractual clauses that could be embedded in various aspects of hardware and software to make the breach of the contract inordinately expensive [5]. These contracts can be self-executing and immutable. Another definition of smart contracts is given by Silvestre et al. [22] who define the smart contract as a piece of computer code that verifies certain actions, and should certain criteria be met, corresponding actions are then carried out. Smart contracts can assist in removing the intermediary part in various use cases, and this may lower transaction costs and allow for low-value transactions to take place [15].

p0170 The advent of smart contracts raises some interesting questions with regard to the legal profession. The enforceability of smart contracts and even the use of the term “contracts” has raised some arguments. According to Jamison and Tariq [10], a traditional contract requires the following elements to be considered a contract:

o0010 **1.** Offer of the contract
o0015 **2.** Acceptance of the contract
o0020 **3.** Binding agreement to execute a lawful action
o0025 **4.** An exchange of value once the action has been carried out
o0030 **5.** All parties involved should have sufficient legal capacity to enter into the contractual agreement.

p0200 Because smart contracts are pieces of immutable, self-enforcing programming code where the authors of the contract can be anonymous or even pseudoanonymous, there are many situations where a smart contract will not meet the criteria listed earlier.

s0045 *1.2.5 ICO and token sales*

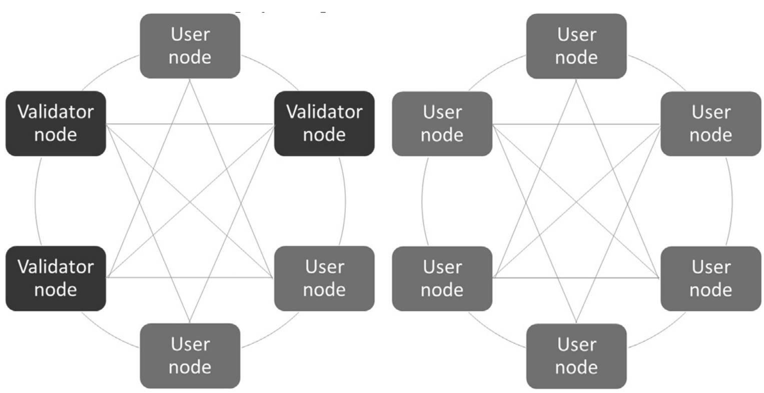
p0205 The introduction of the various cryptocurrencies has allowed the developers to engage in a new form of raising capital called initial coin offerings (ICOs) [5]. In a typical ICO the developers of the cryptocurrency will allow the sale of a set number of tokens (units of the cryptocurrency) to sellers as a means of investment in the cryptocurrency project or a way to raise capital. There are parallels with the well-known initial public offerings (IPOs), but the ICOs do not generally give the investor a portion of the equity of the project. Rather the investors hope that the cryptocurrency will appreciate in value and thus provide them with an adequate return. ICOs are largely unregulated, and this has led to many fraudulent and poorly supported cryptocurrency projects to launch their own ICO [4]. Many of the ICOs that have already been launched suffer from significant problems including underperformance and failing to advance the project past the conceptual stage [10].

s0050 1.3 Characteristics

p0210 This section introduces several characteristics of the blockchain technology and assesses its applicability to the energy sector.

p0215 There are various types of blockchain available, and the choice of which type to use should be made keeping the characteristics of the organization and problem to be solved in mind.

p0220 Blockchains can be split into two types, either public or private. These definitions refer to the one who is allowed to read the content of the blockchain, that is, who can view the content of the transaction history and interact with the blockchain system. Public blockchains are open to anyone to view the transaction data, whereas private blockchains do not allow the general public to view the transaction logs. Blockchains can also be divided along the lines of who can write (add information) to the blockchain otherwise known as validation. Permissionless blockchains allow any node to write and commit information to the blockchain, while permissioned blockchains only allow certain nodes to write to the blockchain [7]. Permissioned ledgers generally have their members known to each other, and this helps facilitate trust in the group of nodes. These types of ledgers do not need to use a distributed consensus mechanism, but they can rather use a predetermined agreement protocol [14]. The difference between a permissioned and permissionless blockchain is shown in Fig. 3 [15]. In the left-hand network, each node has the ability to read and write to the blockchain (shown by the images of the computer and the checked paper). In the right-hand side, only the red nodes can validate transactions. Permissionless networks can be thought of being more decentralized and democratic than permissioned networks, but each network has its advantages and disadvantages, and the choice of network architecture should be made after careful consideration of the project's specifications.



f0020 **FIG. 3** Difference between permissionless *(left)* and permissioned *(right)* blockchain systems. *(Author modified from M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, A. Peacock, Blockchain technology in the energy sector: a systematic review of challenges and opportunities, Renew. Sustain. Energy Rev. 100 (2019) 143–174. https://doi.org/10.1016/j.rser.2018.10.014.)*

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p0225 There are examples of hybrid blockchains that have characteristics of both public and private chains. These blockchains are called consortium blockchains and are often targeted at enterprise use. They include Hyperledger, Corda, and Quorum.

p0230 A large factor in the performance characteristics of a blockchain (scalability, transaction speed and finality, security, and use of resources) is the method used by the blockchain to reach consensus [15]. Choosing the correct consensus mechanism is critical as the mechanism has to be flexible and responsive enough to allow the blockchain to work optimally, but it is the consensus mechanism that also has to protect the blockchain from faulty or malicious nodes, and thus the consensus mechanism has to be resilient enough to protect the blockchain system.

p0235 To an end user a distributed system seems like one unified system, but in reality the different nodes in the system have to coordinate their activities so as to provide a common outcome. This coordination between the various nodes and the systems' fault tolerance are the main challenges for distributed systems. Fault tolerance refers to the ability of the network to sustain some nodes becoming faulty and still remain available.

p0240 Distributed systems are governed by the CAP theorem, also known as Brewer's theorem. This theorem posits that a distributed system cannot have consistency, availability, and partition tolerance simultaneously [14]. Consistency requires that each node in the system have the latest version of the data. Availability requires the system to be operational and functional. The partition tolerance requirement states that the system is capable of surviving a failure of a group of nodes within the system. A common method used to achieve fault tolerance is replication, and consensus mechanisms are used to ensure that the consistency aspect of the CAP theorem is satisfied.

p0245 Blockchains choose to concentrate on availability and partition tolerance, and consistency is not achieved simultaneously with availability and partition tolerance, but it rather is achieved over time, and this is termed eventual consistency [14].

p0250 As blockchain has evolved over the years, there can be three broad categories into which blockchain projects can be classified into according to their complexity and level of autonomy [7]. Cryptocurrencies (such as bitcoin) can be classified as being part of the Blockchain 1.0 family. The introduction of smart contracts is the key defining characteristic of Blockchain 2.0 applications where the first set of autonomous actions can be carried out by the blockchain should certain criteria be met. Blockchain 3.0 is characterized by decentralized autonomous organizations, which take the concept of smart contracts to the next level. These are organizations that are solely run on a collection of smart contracts and a high degree of autonomy. Currently, Blockchain 1.0 and 2.0 applications are most common, and Blockchain 3.0 applications will require further maturation of the technology [7].

p0255 The design and operation of electricity networks are classified as a natural monopoly where the high capital costs, economies of scale, and other barriers to entry provide an advantage to the first mover in the system and restrict access to the market. Often, these first movers are then regulated so as to ensure that consequences of this type of market failure do not impact the customers. This often requires that these agents have unique responsibilities for the correct operation of the networks. These requirements are at odds with the decentralized nature of blockchain systems, and finding a solution to this issue is a key aspect if the blockchain technology is to be successful in the energy sector.

p0260 The hype around blockchain can be thought of as both a help and a hindrance. Blockchain can help move the loci of trust from a central platform operator to trust in the underlying blockchain protocols and programming code [5]. Because blockchain reduces networking costs, it affects the issues of market power of the intermediary, privacy risks, and risks associated with censorship. This may reshape the architecture of the electricity market and create new opportunities for new entrants to take advantage of the new architecture [5]. Blockchain offers the following key characteristics that will be beneficial to recording transactions. The general use case of blockchain has the following characteristics:

u0010 • A database is needed to order and record transactions
u0015 • Multiple users need to use the database to add transactions
u0020 • The ordering of the transactions is crucial
u0025 • There may be malicious actors within the network, which limits trust in the network
u0030 • There is a need for disintermediation [12]

p0290 If there is no need for disintermediation or there is a need for a trusted third party, the use of a blockchain-based system may not be needed as there are significant computation and communication costs associated with implementing a blockchain system [23]. Blockchain is thought to be most useful in a situation where the transaction does not involve a physical exchange [7].

p0295 As has been described in the earlier sections, the blockchain protocol has shown to be very resistant to hackers and other malicious actors. The weak link, therefore, becomes the device connected to the blockchain, and a further weak link is the user of the device.

p0300 There are some characteristics of the blockchain ecosystem that may allow for the creation of systems that steer communities toward socially beneficial actions, and this might help solve issues relating to the tragedy of the commons problem [8]. This aspect of blockchain has received significant attention recently, and this has coined the term “cryptoeconomics” [24]. In short, cryptoeconomics combine cryptography and economic principles to create decentralized peer-to-peer networks that are robust and can thrive in an environment where there are malicious or adversarial peers [24].

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s0055 2. Current and past projects

p0305 The blockchain ecosystem has grown at a rapid rate in the past few years. This section will examine some of the most noteworthy projects that have emerged. Luke et al. [7] states that as of March 2018 the number of organizations working on blockchain in energy numbered 122 and there were 40 projects announced. This number can only be expected to grow. These are listed in Appendix 1 at the end of this chapter.

p0310 One of the most cited projects of blockchain in energy is the Brooklyn Microgrid designed by LO3 Energy. This project consists of a microgrid energy market situated in Brooklyn, New York, and gained significant attention by performing the first-ever blockchain-based peer-to-peer electricity transaction [25]. The project comprises less than 60 participants, and the participants are connected to the existing distribution grid, and when the participants transact, they are not transacting electricity but rather a form of renewable energy certificates [4].

p0315 Another existing project is Grid+, which is based in Texas and aims to give residential consumers better access to participate in wholesale electricity markets [4]. It still has a considerable way to go before reaching its final goal of helping residential consumers manage their bills, trade electricity, and offer their distributed energy assets to help manage the distribution grid; Grid+ can currently assist consumers to manage the component of the bill related to the wholesale costs of electricity, and this is often a small component of the overall bill [4].

p0320 A startup based in the United Kingdom, Electron, is aiming to create a flexibility market for electric power using the blockchain. NRGCoin, an initiative, aimed at helping support the integration of renewable energy by providing incentives for the local production and consumption of renewable energy [23].

p0325 An example of a project funded by both industry and government is the Irish EnerPort project. This project seeks to develop peer-to-peer energy trading networks between microgrids [26].

p0330 While the startup companies who are aiming to disrupt the energy sector by using the blockchain technology may receive a significant amount of media attention, those companies who seek to work along with incumbent entities are most likely to succeed [4]. The key will be to see the blockchain act more of a platform to enable other information technologies and less of an instant solution [4].

p0335 The role of blockchain in energy has not only been explored by startup companies. Incumbent companies in the energy sector have begun to explore how they can use the blockchain technology. A key example of this is the Energy Web Foundation. This foundation aims to accelerate the adoption of the blockchain technology in the energy sector and counts among its affiliate members Centrica, Duke Energy, Engie, E.ON, Shell, TEPCO, and GE [27].

Shafie-khah, 978-0-12-817862-1

p0340 The blockchain system designed by the Energy Web Foundation has a confirmation time of between 3 and 4 s and can handle several thousand transactions per second [15].

p0345 The Enterprise Ethereum Alliance (EEA) was launched in March 2017. This initiative brought together various blockchain startups, research centers, and different Fortune 500 companies. The EEA sought to create an open-source standard for the blockchain [21].

p0350 Another example of a large-scale collaboration is the Hyperledger project that was formed in December 2015 and aims to create an open-source distributed ledger framework to help boost interoperability between blockchain applications and systems [14]. The Hyperledger project is composed of a number of frameworks and tools. There are five frameworks and five projects as of January 2019 [28].

p0355 There are a number of large organizations offering Blockchain as a Service (BaaS). These include Microsoft's Azure, IBM's Bluemix, SAP's HANA and Leonardo blockchain projects, and recently Amazon Quantum Ledger Database and Amazon Managed Blockchain. These tools help ease the difficulty of interacting with a blockchain system, and these projects will be crucial in increasing the mass market adaptation of the blockchain technology.

p0360 It is not only large corporations that are investigating blockchain, but also some political and governmental organizations are investigating the possible use cases of the technology. The largest is the European Union's Blockchain Observatory and Forum. The goal of this forum is to examine the potential impact of the blockchain technology and potential uses of the blockchain technology for the citizens of the European Union [29]. A number of European countries are attempting to position themselves on cutting edge of blockchain technology. These include France, Germany, Austria, Lithuania, Estonia, Spain, and the Netherlands [29]. Funding totaling €30 million has been dispersed by the European Union with an additional €300 million in possible future funding. A report showed that 60% of large corporations are exploring blockchain technology and nearly 90% of international banking executives have initiated exploring the possible impacts of blockchains or distributed ledgers in payment applications [29].

p0365 During the course of writing this chapter, a detailed list of various companies and initiatives working with blockchain in energy was developed. This list is presented in Appendix 1 and lists the primary field of each company and the location of nearly 150 companies and initiatives.

s0060 3. Limitations

p0370 While there have been many examples of the potential benefits of incorporating the blockchain technology in the energy sector, there are still some limitations that will need to be overcome before the technology can make a significant impact in this sector.

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p0375 While not a limitation of the blockchain technology itself, there is an inherent limitation in applying the technology to the electric sector. The electric sector is often characterized by large-scale, centralized systems that make use of both economies of scale and economies of scope. These factors combined with the risk-averse nature of many electric utilities could limit the speed and scale of the blockchain impact in the sector. The fact that there is often a physical transaction coupled with a financial transaction in the energy sector raises some issues with regard to blockchain's potential impact on the sector. This is especially true in the electric power sector as, once injected into the grid, it is very difficult to control and track the electricity from the supplier to the consumer.

p0380 Public and permissionless blockchains would allow the highest number of people to join a blockchain system, but the trade of this increased size is the transaction speed and the high costs of proof of work consensus mechanisms that have dominated the public and permissionless blockchain ecosystem. This trade-off has been termed the "scalability trilemma," and it states that a blockchain can only have a maximum of two of the following three characteristics: decentralization, scalability, and security [7]. Innovation and research will be needed to overcome these challenges. There is some progress being made with different consensus mechanisms such as the Tobalaba network created by the Energy Web Foundation that uses a proof-of-authority consensus mechanism.

p0385 There is a school of thought that states that the security of a blockchain can only be tested once it has grown to such a size that the reward for hacking the system becomes attractive [7]. This could be a challenge for an early project using blockchain in the energy sector. The strength of the network can only be fully tested once it has grown to such a size that it becomes the target of a coordinated attack. A successful attack on such a system would have a significant impact on society given the critical role electricity plays in the modern economy.

p0390 The allocation of legal and technical responsibility of the blockchain also may become an issue should unforeseen events take place such as a security breach [7]. This issue is often compounded due to the lack of a hierarchical structure of the developers of the blockchain. There is often heated debate among the programmers when certain modifications of the underlying code need to be carried out. This problem could also highlight the lack of flexibility of a blockchain once they are deployed, and this issue is made more difficult with the development of DAOs.

p0395 The issue of using a blockchain as a register of physical assets could be an issue should a fork or split of the blockchain take place [7]. Different people having ownership rights of the same asset at the same time could lead to difficult legal issues.

p0400 In cases where smaller systems composed of individuals who already have a degree of trust in each other, the benefits of running a decentralized system of distributed ledgers do not always perform better than a centralized database [11].

Shafie-khah, 978-0-12-817862-1

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p0405 Maintaining trust in the blockchain system is key for its continued survival, but the volatility in the prices of various cryptocurrencies shows that trust and confidence in these systems fluctuate significantly [7]. The volatility of the cryptocurrency prices is also another factor limiting the adoption of cryptocurrencies as a widespread medium of exchange. Splits and forks in the blockchain could also introduce further uncertainty and decrease the trust in the network, and this necessitates very good governance and change management strategies to reduce the possibility of a fork [5].

p0410 Should the energy system develop into one characterized by millions of decentralized energy resources making multiple transactions per day, the need to store all of these transactions in the blockchain may pose a technical challenge because it would be very difficult for each node of the network to store a complete copy of all the transactions [30].

p0415 A partial remedy for the scalability issue could be using off-chain transactions [12]. There are also initiatives such as the Raiden and Lightning networks to improve the speed of the Ethereum and Bitcoin networks, respectively. Sharding or partitioning the blockchain into a number of smaller chains is also another proposal to make the blockchain more efficient [12], although sharding also has its own challenges that need to be overcome before it can be implemented successfully.

p0420 As of January 2019 the Bitcoin blockchain is processing between three and four transactions per second on average, and the Ethereum is processing approximately seven transactions per second [31]. This is much smaller than comparable transaction processing networks such as Visa or Mastercard, which handle roughly 5000 transactions per second.

p0425 As the blockchain ecosystem is still in a nascent stage, the choice of consensus mechanisms and other aspects relating to the blockchain architecture could be difficult for developers to make. So far, there has not been a dominant consensus mechanism or system architecture to emerge, and this may hinder the progress of blockchain developers as they may not know the pros and cons of each system choice [15].

p0430 State channels may offer a way to increase the speed of a blockchain network. These involve opening up a dedicated side chain to record multiple transactions between two parties, and once the trading has been completed, the final accounting is then added to the main blockchain. In this way, there is only one final transaction added to the main chain rather than several intermediate transactions between the same two parties [14].

p0435 One blockchain that aims to tackle the issue of throughput or transactions per second is the EOS blockchain. The developers of this blockchain aim to reach between 6000 and 8000 transactions per second [32]. As of January 2019 the EOS network has reached a maximum of 3996 transactions per second [33].

p0440 The complete removal of trusted intermediaries may not be desirable as they often play other roles in society. Therefore the use of the blockchain

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may force a reinvention of these trusted third parties to concentrate on their other roles in society [7].

p0445 There have been counterintuitive cases where the success of a blockchain has been a hindrance to it as well with the new-found popularity becoming a major issue to the underlying network. An example of this is the CryptoKittie trend that disrupted the Ethereum network toward the end of 2017. A CryptoKittie is a unique digital pet generated by the application's code when two other CryptoKitties are paired together and "breed." Each CryptoKittie is unique and recorded on the Ethereum blockchain. The trend grew rapidly and put severe pressure on the Ethereum network, which slowed the entire network [34]. The explosion in popularity of the CryptoKittie did raise the profile of Ethereum and made it seem more perceivable to the general public. But this rise in profile came at a significant cost, and in December 2017 CryptoKitties made up to 20% of the total Ethereum traffic, and this traffic severely slowed the remaining Ethereum network. The CryptoKittie trend raised doubts on the potential of the Ethereum network to handle vast numbers of transactions from distributed applications, and the network will require further development before it can handle a significant number of transactions [34]. The trend of CryptoKitties lead to a sixfold increase in the volume of Ethereum transactions and showed that Ethereum is currently not able to handle the volume of transactions that large-scale applications will bring [35]. The issues caused by CryptoKitties also had some positive outcomes as more developers realized that there would need to be a significant increase in the transaction processing capacity of the network.

p0450 There also needs to be significant work on developing standards and other means of ensuring interoperability between two or more blockchains [14]. There has been work carried out in this field, most notably the development of the ISO/TC 307 technical committee tasked with the standardization of blockchain and distributed ledger technologies [14]. The Hyperledger project combined with other open-source efforts such as the R3 project and the open-chain standard are working to ensure a common pool of blockchain tools and protocols.

p0455 Self-governance of blockchain systems is also a major challenge facing developers today. The ideals of decentralized, immutable, and pseudoanonymity do not generally make for the easily establishing a robust governance structure and to do this without sacrificing the ideals of a project based on open collaboration between a group of core developers.

s0065 4. Rules and regulations

p0460 There are a number of rules and regulations that already influence the impact of blockchain, not only in the energy sector but also across other sectors. The pseudoanonymity offered by blockchains may fall foul of existing know-your-customer (KYC) and anti-money laundering (AML) rules. These rules may require organizations to expend time and effort to link blockchain accounts to real-world identities [5]. This may require a centralized authority to monitor and verify the names and addresses of the users of a blockchain system that will go against the spirit of decentralized systems.

p0465 Regulators not only do have a responsibility to oversee and safeguard current applications of blockchain but also do have a powerful role in shaping the future growth of blockchain applications. Proactive policy to assist the immature blockchain technology is needed to provide assurances to developers and financers for the blockchain ecosystem to grow and develop. That being said, there is a real need for regulatory policies, which seek to minimize the risks of current users of the blockchain, such as regulating ICOs so as to restrict the number of poorly designed or even fraudulent projects. An example of such policy is the European Union's Digital Single Market and the Declaration on the European Blockchain Partnership [7]. Another example is the joint European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) to develop the CEN-CENELEC Focus Group on Blockchain and Distributed Ledger Technology whose main activity is the development of the ISO/TC 307-Blockchain and Distributed Ledger technologies standard.

p0470 Standards will be necessary as new equipment may need to interact with demand response programs and these types of equipment (household appliances and commercial and industrial equipment) generally have lifetimes of a few years, so they will need to be prepared for future developments in decentralized energy markets.

p0475 There needs to be a balance between ensuring that households and communities have an adequate supply of energy, including in extreme situations, and also promoting other regulatory goals such as promoting the use of low-carbon energy sources. There have been several examples of regulations being passed to allow self-consumption of energy (in France) and allowing the limited peer-to-peer energy trading (in Germany, the Netherlands, and the United States) [12]. Regulatory policies also shape the business models of firms operating in the electric power sector [1]. In some cases, especially distributed energy resources, business models are driven more so by regulatory and policy factors than by technological considerations [1]. There are also issues of creating regulatory dependence among business models, and thus regulations need to be carefully considered.

p0480 Alongside regulations, it is very important to get the tariff design right as this could have significant impacts on the sector and society at large. For example, poorly designed tariffs are thought to have forced electricity consumers in the United Kingdom to pay an additional £1.4 billion pounds per year over the period 2012–15 [36].

p0485 How the blockchain fits into the European Union's General Data Protection Regulations will be an interesting and crucial dynamic to resolve in the coming years. The GDPR states that in certain case user data should be anonymized or

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erased. How this can be done in the blockchain with its permanent and immutable record of transactions may be challenging [4]. The GDPR also allows individuals to have access and control of their data in certain cases that again run against the principles of the blockchain technology [37]. Protection of user data lies at the heart of both the blockchain technology and the GDPR, but the two attempt to solve the problem in drastically different ways, and as such, there have been attempts to interpret the GDPR in a flexible manner so as to allow the blockchain to operate in the European environment [37]. The GDPR also states that data can only be sent to third parties who are outside of the EU if that jurisdiction has equivalent standards for data privacy as the GDPR [7]. This may be an issue for public blockchains with nodes spread across numerous locations as the blockchain cannot direct data to certain locations.

p0490 Blockchain technology may be faced with some short-term reputational impacts due to the perceived issues of bitcoin (and other cryptocurrencies) facilitating illegal activities. This may be difficult to overcome until the public learns more about the blockchain technology and are exposed to successful projects that actively shun the shadow economy that has been known to use cryptocurrencies for illegal activities.

p0495 From a policymaking perspective, it will be key for policymakers to understand the blockchain technology before attempting to make policy to regulate and control it. Following this, it will be imperative that efforts be made to standardize the technology and increase the interoperability of the various networks. Regulatory sandboxes or pilot projects with relaxed regulatory constraints should then be implemented to see how the technology works in the real-world (although small-scale and controlled) environment [4].

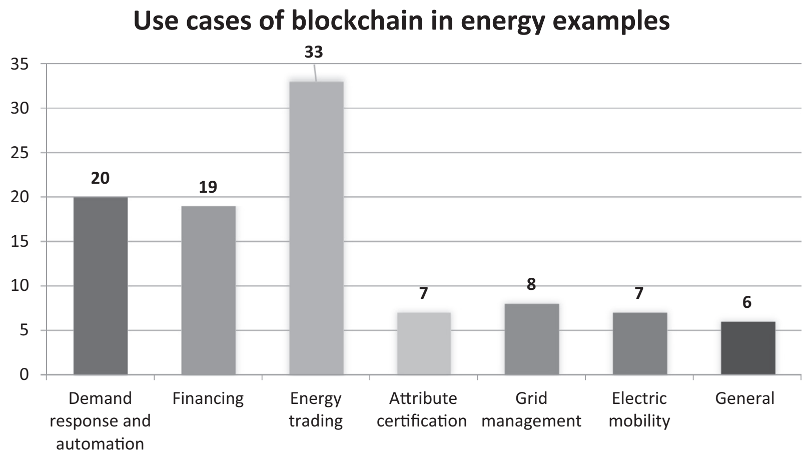
p0500 Regulators should be adaptable and take lessons from other sectors that experience the rapid proliferation of digital technologies that challenged the status quo of that sector (such as the telecommunications industry) [10].

p0505 ICOs have also come under the increased scrutiny of regulatory bodies, especially the Securities and Exchange Commission (SEC) in the United States. The issue of whether or not an ICO is considered a security was a major question surrounding the ICO environment. In March 2018 the head of the SEC confirmed that ICOs were considered securities and thus had to follow the usual rules and regulations of the asset class [38]. Cryptocurrencies do not meet the security definition as stated by the head of the SEC [38].

s0070 5. Applications of BC to energy

p0510 This section briefly touches on the various subsectors within the energy sector that may be impacted by the blockchain technology. This section only provides a brief overview of the various applications of blockchain technology as the remaining chapters of this book examines each of the sectors in more detail.

p0515 When assessing the potential impact of the blockchain technology on the energy sector, there are five areas within the energy sector that may be affected



f0025 **FIG. 4** Breakdown of the different use cases of examples of blockchain in the energy sector. *(Author modified from M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, A. Peacock, Blockchain technology in the energy sector: a systematic review of challenges and opportunities, Renew. Sustain. Energy Rev. 100 (2019) 143–174. https://doi.org/10.1016/j.rser.2018.10.014.)*

as shown in Fig. 4. These are energy trading (wholesale and retail markets), attribute management, demand response, electric mobility, and financing of projects within the energy sector. This section will examine each of these use cases in detail and then provide a short section detailing general considerations regarding the impact of the blockchain technology in the energy sector.

s0075 5.1 Energy trading

p0520 One of the most widely cited applications of blockchain in the energy sector is its potential impact in the energy trading sector. Blockchain could speed up the payment for various services and allow for payment to follow automatically as soon as the transaction has been completed. This could be achieved by using smart contracts. Traditionally the payment process has lagged behind delivery quite significantly, and a whole business sector has emerged to deal with the payment and settlement process.

p0525 The rapid settlement of transactions will become increasingly important because the volume of transactions is expected to grow as more individual households are in a position to produce, consume, and trade electricity [39]. Currently the trading process involves numerous transactions between numerous actors, and this means that the process is ripe for the possible disintermediating effects of blockchain technology.

p0530 Energy trading is a fairly new phenomenon as there was very limited trading taking place before the year 2000. Historical demand figures were used to forecast the demand for electricity with the generators carrying out voltage and frequency control [40]. The liberalization of the European energy markets created a transition from the vertically integrated utility toward a more horizontal market with a large number of both suppliers and buyers of energy products, and this led to a significant rise in the number of transactions carried out. Along with the increased number of transactions, there was a rise in the number of products being traded including both long-term (futures-based) and short-term deals (spot market). In the futures markets, there are both physical and financial products being traded. The financial product sector is where the blockchain could work best as these trades do not involve a physical transfer of goods. Merz [40] suggests that the initial use case for blockchain technology in this sector could be as part of the communications network handling the trades. This could be especially useful in standardizing the information flow between traders. Should the markets make use of one blockchain to coordinate the trades, all traders will need to provide the same information for their trades, which could increase the transparency of these trades. The blockchain could help remove intermediaries in this system, which are often cumbersome and slow the process down.

p0535 The liquidity of the market will be improved should the time taken between the delivery of the energy assets and the associated settlement is reduced [40].

p0540 Those energy trading projects that state that they allow their consumers to choose where their electricity comes from will never be able to actually allow their customers this choice. Their promise does not take into account the nature of the flow of electricity in a network and Kirchhoff's circuit laws [40]. However, should the energy markets incentivize the consumption of locally produced electricity, an increase in the development of generation assets near to demand centers could be seen as opposed to the previous paradigm of locating the generation assets near to their fuel resources (mostly coal and natural gas).

p0545 The current way of handling the trading can result in high transaction costs and operational inefficiencies. A possible example of the blockchain in energy trading has been developed by Ponton. This is the "EnerChain" project, which is a decentralized version of a clearinghouse using the blockchain technology [7].

p0550 Some of the longest lags between delivery of energy and the associated payment occur within imbalance settlement markets with payments taking up to 28 months to be settled [15]. Smart contracts could be utilized to automatically carry out the payment once the delivery of the energy has been received and verified. Smart contracts could also create a more transparent market and reduce other inefficiencies within the existing markets. Accordingly the potential impact of blockchain in this sector has been realized by investors with 57% of the capital raised for blockchain in energy projects being allocated to projects looking to increase the speed taken to verify and execute transactions [7].

p0555 Another aspect of energy trading in which blockchain may have a significant impact is the recording of data associated with the condition of various assets within the network [7]. Additionally, due to its inherent redundancies, blockchain could help protect against the risk of cyberattacks on the electricity network. This risk is only expected to grow as more devices are connected to the Internet and operate at the edge of the grid where it may be difficult to enforce existing cybersecurity measures [6].

p0560 However, using the blockchain in energy trading markets still has some issues to work out. It may still be very difficult to track the flow of electricity in a network so as to verify the transaction between a supplier and consumer of the electricity [41]. Additionally, even if the market allows energy trading agreements to be set up between two parties, these agreements will need to be approved by a central authority once a technical feasibility assessment has been done to prove that the network can handle this transaction. Should the network not be able to handle the agreed transaction, it may be difficult to renegotiate the agreement if smart contracts are used.

p0565 Using the blockchain technology to enable peer-to-peer markets can increase the customer's participation in that market and put the customers at the heart of the energy transition. In these markets, individuals could offer to sell their excess generation or market their flexibility to other market participants. This could help in increasing the penetration of small-scale renewable energy sources and increasing the flexibility of the market. Various use cases for blockchain in energy trading have been presented and include peer-to-peer trading in microgrids, bilateral agreements between producers and consumers, demand response actions, coordination of virtual power plants (VPPs), management of the grid, energy storage management, aiding in the control strategies of DERs, community energy initiatives, and coordinating a power plant portfolio [15]. It is unlikely that the energy system will ever be fully decentralized as there will always be a need for a central authority to manage and control the distribution and transmission grid. Blockchains could also expose consumers to the real price of energy. This could lead to more rational energy choices or increased participation in demand response activities [15].

p0570 The roles played by the different actors in the energy system may also change. The owners of the transmission and distribution (normally the TSO and DSO) will still be responsible for operating and maintaining the physical networks, and they will need to be compensated for that plus their roles as system stabilizers. Each node in a peer-to-peer energy market will need to be responsive to the needs of the grid and react accordingly. These grid needs may include network conditions, prices, and balancing supply and demand [42]. This will increase the onus on the owners of the DERs to provide timely and accurate information to the system operator.

p0575 These factors combine to make it very unlikely that a fully decentralized electricity network that makes use of peer-to-peer energy trading will develop in the next decade. This is because the existing grid, while flawed, does provide services to its customers that a decentralized network may struggle to achieve [4]. As the roles of actors within the electric power system change and evolve over time, there may be scope for blockchain systems that work with the incumbent utilities to help manage the grid [4]. Blockchain is likely to reduce the barriers to entry for individuals to participate in an energy trading market; this increases both transparency and liquidity of the market. Blockchain also allows for more flexible generation portfolios with a diverse set of resources and numerous transactions occurring between the market participants [43].

s0080 5.2 Environmental attribute management

p0580 Using blockchain systems to help manage the environmental attributes (systems that reliably verify the origin of various units of electricity), this sector encompasses markets for products such as guarantees of origin, provenance certificates, and renewable energy credits). The generic term of Energy Attribute Certificates (EACs) will be used in this section. The EAC sector provides a solid foundation for blockchain systems. The existing systems are generally complicated and require numerous trusted third parties to ensure compliance, open to fraud and errors; the markets are thus often slow and cumbersome with high barriers to entry, and there is no physical transfer of goods in this market. Rather the EAC markets revolve around providing verifiable proof that a particular individual has the ownership rights of a particular attribute. Challenges associated with the current system also include having to rely on costly manual audit processes, the limited geographical scope of existing systems, and opaque management practices [7].

p0585 Using blockchain to run these markets may increase the amount of capital invested in clean energy technologies and therefore help reduce emissions relating to the energy sector [4]. The European Union Emissions Trading System (EU ETS) requires nearly 11,000 thermal power plants with capacities of over 20 MW to purchase emission certificates to account for their related CO_2 emissions [44]. Lowering the transaction costs of participating in such attribute markets could also allow for the introduction of smaller power plants and even include other sectors of the economy that have traditionally been left out of such attribute markets such as transportation or residential heating [44]. Costs of interacting with the current markets can run into thousands of euros per year, and this acts as a large barrier to entry for many smaller actors who would otherwise like to participate in the market [16].

p0590 There are concerns that the future of attribute markets is not so positive in the long term as, should the global economy switch to 100% renewable energy sources, there will not be a need to record the environmental attributes of each unit of electricity [44]. That being said, attribute markets are an effective tool to enable that transition.

p0595 Like in other sectors, blockchain technology holds the promise to reduce transaction costs. In situations where the allocation of externalities plays an important role (such as emission trading schemes), lowering the transaction costs can increase the efficiency of the outcome and bring it closer to being the Pareto efficient outcome as is described by the Coase theorem [45]. Quantifying and monitoring emission target are a crucial pillar in any

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climate change mitigation policy, and the blockchain can help to quantify and monitor these emissions.

p0600 There are examples of initiatives using the blockchain technology in the field of monitoring and verifying environmental attributes of energy. One of these examples is SolarCoin, which is a cryptocurrency that can act as a guarantee of origin system by using proof of generation [16]. Proof of generation means that, for every 1 MWh that a solar PV system generates, the owner of the system is awarded one SolarCoin, and these SolarCoins can be traded at a later stage.

p0605 There is also a pilot project being run in Thailand to examine the effectiveness of blockchain applications in this sector. The project is being developed by South Pole, ixo Foundation, and Gold Standard. The project consists of 10 solar farms and seeks to examine the role of blockchain in the monitoring and verification of information relating to carbon credits [46].

s0085 5.3 Demand response

p0610 Another major part of the energy system that the blockchain could impact is demand response (DR). Demand response programs could be encoded in smart contracts and shared among the participants in a given location. This could help automate the demand response program as each individual could set their preferences and advanced machine learning algorithms could help predict the load profile of each household so as to provide the system operator with the most up-to-date information regarding the available demand that could be utilized. In this example, smart contracts can operate as a decentralized control strategy. There may also be markets for ancillary services (such as voltage regulations and reactive power control) where the blockchain system and smart contracts could help activate, monitor, and report the results in a verified, immutable, and automatic manner. Smart contract with their ability to operate automatically and very quickly may help issues relating business models relating to residential demand response [1]. Coordinated dispatch of demand response from DER devices could help utilities defer expensive upgrades or expansion of the distribution grid, and the demand response effort of DERs could also assist in grid management by providing ancillary services [4].

p0615 It is estimated that there could be approximately 21 billion smart devices connected to the Internet by the year 2020 with nearly a large portion of those devices having a direct impact in the energy sector (such as smart meters, thermostats, and other devices) [2]. This number of devices will provide a significant amount of demand response capacity if it is harnessed and utilized correctly. The concept of the smart grid requires that devices communicate between themselves in an organized and automatic manner and these devices could respond to different signals related to energy price, grid needs, or renewable resource availability [15]. The number of devices and transactions would

Shafie-khah, 978-0-12-817862-1

make centralized systems unwieldy and inefficient, and thus decentralized decision-making and control could provide significant benefits [15].

p0620 There are a number of issues that need to be overcome before this future can be realized. It will be necessary to develop power electronic devices that can communicate with each other and record information to the blockchain system, and these devices will need to be able to measure the demand of various devices in each household. Combined with this technical challenge, there is a societal challenge that will also need to be addressed, and this is the issue of data privacy. It is unclear how comfortable consumers would be sharing the data related to the usage of their household devices [15].

p0625 In a similar vein to the previous two use cases of blockchain in energy, the barriers to entry into demand response markets can be lowered, and this would significantly increase the size of the market. For the United Kingdom, this larger demand response market could unlock an estimated £1 billion in savings, a net savings of £1.4–2.4 billion per year by 2030, and an overall saving of £17–40 billion by 2050, and these cost savings are reached through a combination of reduced capital expenditure on generating assets, lower operations and maintenance costs, reduced network upgrades, and lower costs for security of supply [47].

s0090 5.4 Electric mobility

p0630 Blockchain technology also has the ability to play a major role in electric mobility (EM) sector [15]. In the EM sector the most discussed roles of the blockchain technology are recording the transactions relating to charging of the vehicles and the creation of smart contracts to help electric vehicles offer grid services to the distribution system operator. The decentralized nature of transport (with numerous vehicles, drivers, and dispersed charging infrastructure) makes applying the blockchain technology an attractive option. Using blockchains to help manage electric mobility services will reduce the need for a central authority to manage the vehicles (if they are owned by a ride-sharing platform) and the charging infrastructure and improve the system resilience, and the blockchain can also help create efficient markets in this sector [15]. The major concerns of using this technology in this sector are related to the privacy and security of data. The electrification of mobility is helping to bring together the electric power and transport sectors [4].

s0095 5.5 Financing

p0635 Blockchain technology could increase the size and liquidity of capital available for various projects in different sectors, including projects in the energy sector. It can do this by lowering the barriers to entry to these markets and thus making them available to smaller investors who would normally be locked out of such capital pools. Blockchain could also impact the financing of energy projects

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through the so-called "tokenization" of assets. Tokenization converts the ownership rights to a particular asset to a digital token that can then be split up into a number of different parts so that individual investors can own a portion of the physical asset. This way a single investor can buy a portion of a tokenized renewable energy project, and their return will be proportional to the percentage of the asset that they own. Apart from tokenization of assets, cryptocurrencies can be designed to reward certain types of behavior, and this could be used to spur individuals to act in a beneficial manner when they might otherwise not do so.

s0100 5.6 General considerations

p0640 The blockchain also has the potential to impact certain activities that cut across numerous areas in the energy sector. These activities include increasing the speed and accuracy of data recording, lowering the price of verification of data, reducing the need for a number of intermediaries, and automation of existing processes. This will mean that, by using the blockchain in the energy sector, costs could be reduced, and this could translate into lower fees and levies for the end customer.

p0645 Tracking shipments of oil and gas could be made easier using the blockchain as the technology can help digitize documents and improve supply chain management. This has already been seen in other sectors such as the maritime and aviation. In the overlap between the maritime, aviation, and energy sectors, the use of blockchain technology could provide significant benefits when it comes to dealing with bunker fuel shipments. There are large amounts of high value product in the bunker fuel market, and it is necessary to accurately track and record transactions to reduce the possibility of fraud occurring [48].

p0650 The blockchain may help the electricity network become more resilient, secure, and reliable as decentralized systems do not have single points of failure as it is common in large-scale centralized systems [7,39].

p0655 The blockchain has been touted as a revolutionary technology that will drastically transform the way we carry out our daily lives, but the technology should never be viewed or used in isolation. It should form part of a diverse set of technologies that should be tailored to suit the characteristics of the problem at hand. The blockchain can be used in such a way that it has some positive benefits on the energy sector, but it is unlikely that it will create a massive restructuring of the energy sector in the short to medium term. As with most new technologies, some proponents of it believe that it will revolutionize the existing industry, and then, on the other hand, there are always critics of the technology who see it nothing more than a passing fad. Blockchain certainly has received significant attention from both sets of actors and the impact of the technology in the energy sector will fall somewhere between the two extreme camps.

Shafie-khah, 978-0-12-817862-1

s0105 6. Conclusion

p0660 This chapter has presented an overview of the potential impacts of the blockchain technology in the energy sector. This chapter has introduced the technology and the context surrounding not only the technology but also the ongoing energy transition. The combination of these two events has shown that the blockchain technology could play a significant role across numerous sectors in the future energy system.

p0665 This chapter has identified five areas within the energy sector where the blockchain technology could play a significant role. These applications were energy trading, environmental attribute management, demand response, electric mobility, and financing. Within the energy trading subsector, there are clear parallels between the blockchain technology and the operation of decentralized energy networks; however, there are still major challenges to overcome. Physical flows of electricity are incredibly hard to track, and it is not possible to prove the origin of the electricity consumed by an individual. The rise of distributed energy resources will cause the energy system to become more decentralized in the future, and electricity trading will also become more decentralized, and it is unclear just exactly what role the blockchain will play in decentralized energy trading.

p0670 With regard to blockchain's role in helping manage the environmental attributes of the various products in the energy sector, the role is more clearly defined, and the path to adoption may be easier than blockchain's use in energy trading. This is chiefly down to the fact that there is no need for a physical transfer of an asset within trading environmental attribute certificates. There is potential for the blockchain to speed the process of trading environmental certificates by removing some of the middlemen involved in the sector.

p0675 The two applications, demand response and electric mobility, could also benefit significantly from the blockchain technology, especially from the use of smart contracts to enable decentralized trading platforms for demand response and electric mobility, respectively. These platforms could open up these two fields to a number of small consumers or community energy initiatives by lowering the existing barriers to entry of the two markets.

p0680 The lowering of entry barriers and also the lowering of verification costs could also allow the blockchain technology to have a significant impact in the financing of energy projects. Tokenization of energy projects holds some interesting applications, and it could be used to finance various projects within the energy sector.

p0685 That being said, there are some major challenges that need to be overcome before the technology can realize its full potential. Not all of these challenges are related to the technical characteristics of the blockchain technology. Some of these challenges relate to the regulatory aspects of its deployment in the energy sector, and other challenges relate directly to the nature of the energy system.

p0690 Currently, there seem to be two schools of thinking relating to the blockchain's effect on the energy system. On the one hand, there are the blockchain advocates who believe that the technology will revolutionize the current operations of the energy system. On the other hand, there is a group who sees the technology as a passing fad with roots in illegal activities and get-rich-quick schemes. As the technology matures and society learns more about it and how to use it, it is hoped that these two camps can come closer together and work toward a middle ground where the positive effects of the technology are truly felt, not only in the energy system but also in the society as a whole. Proactive regulation is key to helping achieve this goal, and further research will key, especially using pilot projects, to investigate how the technology works in the real world.

s0100 Acknowledgment

p4000 M. Gough, S. Santos, and J.P.S. Catalão acknowledge the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under POCI-01-0145-FEDER-029803 (02/SAICT/2017).

s0110 Appendix 1: Examples of companies using the blockchain technology in the energy sector

t0010 **Blockchain companies working in the energy sector.**

	Company	Sector	Location
1	4New	Cryptocurrencies, tokens, and investment	The United Kingdom
2	Aizu Laboratories	Grid management	Japan
3	Alastria	General purpose initiatives and consortia	Spain
4	Alliander and Spectral Energy (Jouliette at De Ceuvel)	Decentralized energy trading	Netherlands
5	Alliander (Alva)	Decentralized energy trading	Netherlands
6	Alliander (Charge Ledger)	Electric e-mobility	Netherlands
7	Assetron Energy	Cryptocurrencies, tokens, and investment	Australia
8	Bankymoon	Metering, billing, and security	South Africa
9	BAS Nederland	Metering, billing, and security	Netherlands
10	BCDC (Blockchain Development Company)	Cryptocurrencies, tokens, and investment	The United Kingdom
11	BCPG Group	Decentralized energy trading	Thailand
12	BittWatt	Decentralized energy trading	Romania

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Blockchain companies working in the energy sector—cont'd

	Company	Sector	Location
13	BLOC (EnergyBlock and Community Power)	Decentralized energy trading	Denmark
14	Blockchain Futures Lab	General purpose initiatives and consortia	The United States
15	Blockchain Research Lab	General purpose initiatives and consortia	n/a
16	BlockLab	General purpose initiatives and consortia	Netherlands
17	Bouygues Immobilier and Stratumn	Decentralized energy trading	France
18	BTL	Decentralized energy trading	Canada and the United Kingdom
19	Car eWallet	Electric e-mobility	Germany
20	CarbonX	Green certificates and carbon trading	Canada
21	CGI and Eneco	Metering, billing, and security	Netherlands
22	Clearwatts	Decentralized energy trading	Netherlands
23	ClimateCoin	Green certificates and carbon trading	Switzerland
24	Conjoule	Decentralized energy trading	Germany
25	COSOL	Decentralized energy trading	Brazil
26	DAISEE	IoT, smart devices, automation, and asset management	France
27	Dajie	IoT, smart devices, automation, and asset management	The United Kingdom
28	DAO IPCI (MITO)	Green certificates and carbon trading	Russia
29	Department of Energy, The United States	Metering, billing, and security	The United States
30	Department of Energy, The United States	IoT, smart devices, automation, and asset management	The United States
31	Divvi	Decentralized energy trading	Australia
32	Dooak	Cryptocurrencies, tokens, and investment	Brazil
33	Drift	Decentralized energy trading	The United States
34	EcoCoin	Cryptocurrencies, tokens, and investment	Netherlands
35	Elbox	Decentralized energy trading	Switzerland

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Shafie-khah, 978-0-12-817862-1

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Blockchain companies working in the energy sector—cont'd

	Company	Sector	Location
36	ElectriCChain (SolarCoin)	IoT, smart devices, automation, and asset management	Andorra
37	Electrify.Asia	Decentralized energy trading	Singapore
38	Electron	Metering, billing, and security	The United Kingdom
39	Electron	Grid management	The United Kingdom
40	Elegant	Metering, billing, and security	Belgium
41	eMotorWerks	Electric e-mobility	The United States
42	Enbloc	Decentralized energy trading	The United States
43	Endesa Energia (Blockchain Lab)	General purpose initiatives and consortia	Spain
44	enercity	Metering, billing, and security	Germany
45	ENERES	Decentralized energy trading	Japan
46	EnergiMine	Cryptocurrencies, tokens, and investment	The United Kingdom
47	Energo Labs	Decentralized energy trading	China
48	Energo Labs	Electric e-mobility	China
49	Energy Bazaar	Decentralized energy trading	India
50	Energy Web Foundation	General purpose initiatives and consortia	Switzerland
51	Energy21 and Stedin	Decentralized energy trading	Netherlands
52	Energy-Blockchain Lab and IBM	Green certificates and carbon trading	China
53	EnerPort	Decentralized energy trading	Ireland
54	Enervalis (NRGCoin)	Cryptocurrencies, tokens, and investment	Belgium
55	Engie	Metering, billing, and security	France
56	EnLedger	Cryptocurrencies, tokens, and investment	The United States
57	Envion	Cryptocurrencies, tokens, and investment	Germany
58	EU Blockchain Observatory and Forum	General purpose initiatives and consortia	EU
59	Eurelectric (Blockchain Discussion Platform)	General purpose initiatives and consortia	EU
60	EverGreenCoin	Cryptocurrencies, tokens, and investment	The United States

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Blockchain companies working in the energy sector—cont'd

	Company	Sector	Location
61	Everty	Electric e-mobility	Australia
62	Evolve Power	Grid management	The United States
63	Farad	Cryptocurrencies, tokens, and investment	UAE
64	Filament	Grid management	The United States
65	Filament	IoT, smart devices, automation, and asset management	The United States
66	Fortum	IoT, smart devices, automation, and asset management	Finland
67	Freeelio (AdptEVE)	IoT, smart devices, automation, and asset management	Germany
68	Green Energy Wallet	Cryptocurrencies, tokens, and investment	Germany
69	Green Running (Verv)	IoT, smart devices, automation, and asset management	The United Kingdom
70	Green Running (Verv)	Decentralized energy trading	The United Kingdom
71	Greeneum	Decentralized energy trading	Israel
72	Greeneum	Cryptocurrencies, tokens, and investment	Israel
73	Grid Singularity	Green certificates and carbon trading	Austria
74	Grid Singularity	Grid management	Austria
75	Grid+	Decentralized energy trading	The United States
76	Grünstromjeton	Cryptocurrencies, tokens, and investment	Germany
77	Hive Power	Decentralized energy trading	Switzerland
78	HydroMiner	Cryptocurrencies, tokens, and investment	Austria
79	IBM and Linux Foundation (Hyperledger)	General purpose initiatives, and consortia	The United States
80	ImpactPPA	Cryptocurrencies, tokens, and investment	The United States
81	Innogy MotionWerk (Share&Charge)	Electric e-mobility	Germany
82	Intrinsic ID and Guardtime	IoT, smart devices, automation, and asset management	The United States
83	Inuk	Cryptocurrencies, tokens, and investment	France

Continued

Blockchain companies working in the energy sector—cont'd

	Company	Sector	Location
84	KEPCO	Decentralized energy trading	Japan
85	LO3 Energy	Decentralized energy trading	The United States
86	Local-e	Cryptocurrencies, tokens, and investment	The United States
87	Marubeni (Coincheck Denki)	Metering, billing, and security	Japan
88	M-PAYG	Metering, billing, and security	Denmark
89	MyBit	Cryptocurrencies, tokens, and investment	Switzerland
90	Nasdaq New York Linq	Green certificates and carbon trading	The United States
91	OLI	IoT, smart devices, automation, and asset management	Germany
92	Omega Grid	Decentralized energy trading	The United States
93	OneUp	Decentralized energy trading	Netherlands
94	OurPower (CEDISON)	Grid management	The United Kingdom
95	Oursolargrid & ITP	Decentralized energy trading	Germany
96	Oxygen Initiative	Electric e-mobility	The United States
97	PetroBloq	Decentralized energy trading	Canada
98	Platinum Energy Recovery	Decentralized energy trading	Singapore
99	PONTON (EnerChain)	Decentralized energy trading	Germany
100	PONTON (GridChain)	Grid management	Germany
101	Poseidon	Green certificates and carbon trading	Switzerland
102	Power Ledger (EcoChain)	Decentralized energy trading	Australia
103	Power Ledger	IoT, smart devices, automation, and asset management	Australia
104	Power Ledger	Electric e-mobility	Australia
105	Power Ledger	Green certificates and carbon trading	Australia
106	Power Ledger	Grid management	Australia
107	Power-ID	Decentralized energy trading	Switzerland
108	PROSUME	Metering, billing, and security	Switzerland

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Blockchain companies working in the energy sector—cont'd

	Company	Sector	Location
109	PROSUME	Cryptocurrencies, tokens, and investment	Switzerland
110	PROSUME	Decentralized energy trading	Switzerland
111	PROSUME	Grid management	Switzerland
112	PROSUME	Electric e-mobility	Switzerland
113	PRTI	Cryptocurrencies, tokens, and investment	The United States
114	Pylon Network	Metering, billing, and security	Spain
115	Pylon Network	Decentralized energy trading	Spain
116	Restart Energy	Decentralized energy trading	Romania
117	Slock.it	IoT, smart devices, automation, and asset management	Germany
118	Slock.it	Electric e-mobility	Germany
119	Solar bankers (SunCoin)	Decentralized energy trading	Singapore
120	Solar DAO	Cryptocurrencies, tokens, and investment	Israel
121	SolarChange (SolarCoin)	Cryptocurrencies, tokens, and investment	Andorra
122	SP Energy Networks, SSEN, SP Distribution, SP Manweb, and UK Power Networks	Grid management	The United Kingdom
123	Spectral Energy	Decentralized energy trading	Netherlands
124	STROMDAO	Decentralized energy trading	Germany
125	SunChain (TECSOL and Enedis)	Metering, billing, and security	France
126	SunContract	Decentralized energy trading	Slovenia
127	Swytch	IoT, smart devices, automation, and asset management	South Korea
128	Tavrida Electric	IoT, smart devices, automation, and asset management	Russia
129	TenneT and sonnen	Grid management	Netherlands
130	TenneT and Vandenbron	Grid management	Netherlands
131	The Sun Exchange	Cryptocurrencies, tokens, and investment	South Africa
132	TOBLOCKCHAIN	Decentralized energy trading	Netherlands
133	toomuch.energy	Decentralized energy trading	Belgium

Continued

Blockchain companies working in the energy sector—cont'd

	Company	Sector	Location
134	ubitricity	Electric e-mobility	Germany
135	VAKT and partners (including BP, Shell, and Statoil)	Decentralized energy trading	The United Kingdom
136	Vattenfall (Powerpeers)	Decentralized energy trading	Netherlands
137	Vector Energy (EcoChain)	Decentralized energy trading	New Zealand
138	Veridium Labs	Green certificates and carbon trading	Hong Kong
139	Volt Markets	Decentralized energy trading	The United States
140	Volt Markets	Green certificates and carbon trading	The United States
141	Wanxiang	IoT, smart devices, automation, and asset management	China
142	WePower	Cryptocurrencies, tokens, and investment	Gibraltar
143	Wien Energie	Decentralized energy trading	Austria
144	Wirepas	IoT, smart devices, automation, and asset management	Finland
145	Wuppertal Stadtwerke (Tal.Markt)	Decentralized energy trading	Germany
146	XinFin	Cryptocurrencies, tokens, and investment	Singapore
147	XiWATT	Cryptocurrencies, tokens, and investment	The United States

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