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Blockchain technology in the energy sector: A systematic review of challenges and opportunities

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ABSTRACT

Blockchains or distributed ledgers are an emerging technology that has drawn considerable interest from energy supply firms, startups, technology developers, financial institutions, national governments and the academic community. Numerous sources coming from these backgrounds identify blockchains as having the potential to bring significant benefits and innovation. Blockchains promise transparent, tamper-proof and secure systems that can enable novel business solutions, especially when combined with smart contracts. This work provides a comprehensive overview of fundamental principles that underpin blockchain technologies, such as system architectures and distributed consensus algorithms. Next, we focus on blockchain solutions for the energy industry and inform the state-of-the-art by thoroughly reviewing the literature and current business cases. To our knowledge, this is one of the first academic, peer-reviewed works to provide a systematic review of blockchain activities and initiatives in the energy sector. Our study reviews 140 blockchain research projects and startups from which we construct a map of the potential and relevance of blockchains for energy applications. These initiatives were systematically classified into different groups according to the field of activity, implementation platform and consensus strategy used.[1] Opportunities, potential challenges and limitations for a number of use cases are discussed, ranging from emerging peer-to-peer (P2P) energy trading and Internet of Things (IoT) applications, to decentralised marketplaces, electric vehicle charging and e-mobility. For each of these use cases, our contribution is twofold: first, in identifying the technical challenges that blockchain technology can solve for that application as well as its potential drawbacks, and second in briefly presenting the research and industrial projects and startups that are currently applying blockchain technology to that area. The paper ends with a discussion of challenges and market barriers the technology needs to overcome to get past the hype phase, prove its commercial viability and finally be adopted in the mainstream.

1. Introduction

Energy systems are undergoing rapid changes to accommodate the increasing volumes of embedded renewable generation, such as wind and solar PV. Renewable energy sources (RES) have undergone massive development in recent years, enabled by privatisation, unbundling of the energy sector and boosted by financial incentives and energy policy initiatives. In 2016, 24.6% of the UK gross electricity consumption was generated by RES, mainly from onshore and offshore wind farms and PV solar plants, accounting for 44.9% and 12.5% of the total 35.7 GW installed RES capacity, respectively [1]. RES are variable, difficult to predict and depend on weather conditions, hence raise new challenges in management and operation of electricity systems, as more flexibility measures are required to ensure safe operation and stability [2]. Flexibility measures include the integration of fast-acting supply, demand response and energy storage services [3]. Adding to the transformational change caused by distributed energy resources (DERs) and renewables, energy systems are on the brink of entering the digital era as shown by the massive deployment of smart meters in numerous countries [4]. In the UK alone, 53 million electricity and gas smart meters

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[1] A summary of the research projects reviewed in this study can be found in the Appendix A.

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are planned to be installed by 2020, one for every home and small business [5]. To achieve ambitious emission reduction goals, energy systems will need significant investment. It is estimated that in the EU alone, the transition towards a more sustainable and secure energy system would require an investment of €200 billion per year for generation, network and energy efficiency development [6]. $2 trillion in electricity network upgrades will be required by 2030 in the US [7]. To moderate required investment smart management and control need to be adopted, tasks that are increasingly challenging as energy systems are growing to become more active, decentralised, complex and 'multi-agent', with an increasing number of actors and possible actions. Advanced communication and data exchanges between different parts of the power network are to an increasing extent required, making central management and operation more and more challenging. Local distributed control and management techniques are required to accommodate these decentralisation and digitalisation trends [8]. Blockchains or distributed ledger technologies (DLT), were primarily designed to facilitate distributed transactions by removing central management. As a result, blockchains could help addressing the challenges faced by decentralised energy systems.

Blockchains are shared and distributed data structures or ledgers that can securely store digital transactions without using a central point of authority. More importantly, blockchains allow for the automated execution of smart contracts in peer-to-peer (P2P) networks [9]. They can alternatively be seen as databases that permit multiple users to make changes in the ledger simultaneously, which can result in multiple chain versions. Instead of managing the ledger by a single trusted centre, 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.

Blockchain technology is primarily known from cryptocurrency applications that are recently experiencing an unprecedented rise with market capitalisation surpassing at the time of writing $335b [10]. While opinions on the long term future of cryptocurrencies may be divided, several key applications have been identified by numerous sources. A report by the UK Government [11] states that blockchains might have the capacity to '*reform our financial markets, supply chains, consumer and business-to-business services, and publicly-held registers*'. Potential applications spread from asset registries and transfer of ownership of hard assets [9] to secure recording of intangible assets. Swan [9] envisions these assets as any type of information, reputation or online voting systems. Research works from the financial sector discuss blockchain applications in the banking sector and state that blockchain-enabled platforms can facilitate financial transactions between different financial institutions and make payments faster by speeding up confirmation times [12]. Other applications may improve transparency in supply chain records with certification of manufactured products or diamonds certification [13]. In fact, the variety of applications proposed is such that Tapscott and Tapscott [14] *compare blockchains to the advent of the Internet* and state they could prove to be a technological breakthrough, bringing about significant process optimisation and novel business models. The potential lies on the fact that blockchain or distributed ledger technologies (DLT) can redefine digital trust and can remove intermediaries forming a new paradigm of management that can potentially disrupt traditional forms of governance [15]. The disruptive nature lies on the potential of replacing top-down control with consensus and also in the underlying philosophy of distributed consensus, open source, transparency and community based decision-making [11]. According to the research institute of the Finnish economy [16], these characteristics could instigate further societal changes and implications. According to a recent Gartner report [17], blockchain technologies have already surpassed the peak of inflated expectations in the hype cycle and are predicted to be 2–5 years from mainstream adoption.

Along with use cases in various sectors, the potential of blockchains in the energy industry has just started to be realised as shown by the increasing number of startups, pilots, trials and research projects. A survey of the German Energy Agency [18] on the views of energy decision-makers shows that near 20% believe that blockchain technology is a game-changer for energy suppliers. The survey was based on the views of 70 executives working in the energy sector including utility companies, energy suppliers, network operators, generators and aggregators. More than half of survey participants plan or have already undertaken initiatives for blockchain innovation. Several energy utility companies have taken interest in exploring the potential benefits of distributed ledger technologies (DLT), as an enabling technology for low-carbon transition and sustainability [19]. Moreover, according to senior consultancy and commercial reports by Deloitte [20] and PWC [21], blockchains have the potential of radically disrupting energy related products and commodities, as they become digital assets that can be traded interoperably.

Early research initiatives and startups indicate that blockchain technology could potentially provide solutions to some of the challenges faced by the energy industry. Requirements for future energy systems can be summarised by three key principles: *decarbonisation*, *decentralisation* and *digitalisation*, with a shift to empower consumers, a pillar for both EU [6] and UK policy [22]. However, current structure of energy and electricity markets is inadequate to achieving this vision, as small players' participation in the markets is practically excluded and incentives for active consumer participation have so far proved not sufficient. Early blockchain developers are establishing transactional digital platforms that can be completely decentralised and can enable P2P energy trading. They are developing local energy marketplaces and Internet of Things (IoT) applications that can play a significant role in the vision of the smart grid [23,24]. According to PWC [21], energy firms are increasingly reporting higher energy costs and lower revenues. At the same time utilities face demands for increasing transparency by the regulatory authorities [25]. As a result, any possibility of cost savings and efficiency improvement in the operation of energy systems and markets can prove significant and is worth investigating.

Moreover, potential gains in transparency and competition could benefit other key policy targets related to energy affordability and fuel poverty [26]. According to a UK government report by the Competition and Markets Authority [25], poorly designed tariff prices and lack of mobility in the marketplace have led electricity consumers to pay £ 1.4 billion on average a year in excessive prices for the period 2012–2015. We note that UK retail electricity prices have increased in recent years irrespectively of wholesale electricity prices[2] [27], indicating that there is significant room for improvement. A commercial report by Deloitte [20] states that blockchain-enabled transactional digital platforms could offer operational cost reductions, increased efficiency, fast and automated processes, transparency and the possibility of reducing capital requirements for energy firms. Cost savings potential is not restricted to utilities and can be relevant to energy consumers and prosumers [28], who are facing increasing energy prices and removal of RES incentives, respectively. Solutions promised by blockchains, such as P2P trading in local or consumer-centric marketplaces [29] could potentially lead to cost savings for energy consumers.

On the other hand, blockchain technologies need to address several

[2] According to a Competition and Markets Authority report [25], to a large extent, UK energy residential tariffs are determined by wholesale energy costs (about 40% for electricity and 50% respectively for gas), followed by network costs (about 25%). The costs associated with retailing (including a profit margin) are around 20% of the costs of supplying electricity and gas to domestic customers.

issues before achieving larger adoption. One key challenge is that of scalability and cost, while maintaining desired properties of decentralisation and security. Other emerging issues relate to user anonymity, privacy and the governance of blockchain systems, which often goes against traditional practices adopted by governments and industry. Development efforts in the blockchains and energy area are ongoing, and have been documented in a number of industrial white papers and reports, produced mainly by established consultancy companies. However, we argue a systematic and technically-informed approach, using a neutral, academic standpoint, is still required to evaluate the relevance and applicability of this novel technology to the energy sector. Our work aims to bridge this knowledge gap by providing a timely and comprehensive review. More specifically, the contributions of our work are:

- First, we provide an overview of the fundamental principles of distributed ledger technologies (DLT), discussing different system architectures and consensus algorithms that determine critical technical characteristics of blockchain systems. A substantial amount of current knowledge on blockchains comes not only from traditional academic sources, such as journals and conference proceedings, but forums, blogs, wikis, white papers and industrial reports. The first part of our paper distills key information from these sources, to provide the reader with an in-depth understanding of the broad DLT topic before moving into energy use cases. We discuss, in detail, the benefits and drawbacks of each type of technology and its suitability for a range of use cases.
- Next, we turn our attention in the energy sector and review a number of notable use cases and business opportunities for blockchain innovation. For each of these use cases, we discuss the problems that blockchain technologies can address, as well as the potential problems and drawbacks that must be overcome for blockchain technologies to be implementable in that use case.
- Third, we provide an in-depth, systematic review of current blockchain developments by commercial startups and research organisations. Our study contains 140 blockchain research projects and initiatives undertaken by companies and research organisations. Recent work in this area has been documented in a number of recent industrial reports. Most notably, a comprehensive catalogue of 90 companies pursuing applications in the energy sector was published by SolarPlaza [30]. Over 10 blockchain pilot projects, deployed in collaboration with several municipal authorities were discussed in a report by EnergyCities [31]. A few notable use cases are also discussed in other consultancy reports [20,21]. Our work differs substantially from these sources, by extending the review to considerably more case studies. In addition, we formally classify these initiatives according to their specific field of activity and technical characteristics, which are not covered in these commercially-commissioned studies. To our knowledge, this paper is one of the first academic, peer-reviewed studies to provide a systematic review of blockchain activities in the energy systems field.
- Finally, we discuss the findings of our study and future development of the technology. We also discuss a framework on the adoption of the technology, limitations, market barriers and the potential for larger implications that might emerge with mainstream use of blockchains.

The remainder of the paper is organised as follows: Section 2 provides a background and conceptual description of blockchain technologies. We discuss foundational principles of the technology such as cryptography, smart contracts, distributed consensus and system architectures. We also briefly introduce Bitcoin, the largest and most prevailing blockchain application, and Ethereum, a blockchain-enabled platform in which the majority of energy applications rely on. In addition, we discuss evaluation criteria for suitability of blockchain applications. Next in Section 3, we turn our attention to the energy sector and discuss potential use cases where blockchains can prove beneficial. Section 4 provides a systematic review of blockchain commercial and research activities. We formally classify use cases, pilot projects, trials and startups according to their field of activity, blockchain platform and consensus algorithm used. Finally, Section 5 provides a discussion on limitations, market barriers and future development and Section 6 concludes this work.

2. Blockchain technology conceptual background

Section 2 provides a detailed overview on blockchains, how the technology works and what are its key elements. We provide in more detail types of system architectures and distributed consensus, as these are most critical for determining the technical characteristics of blockchain systems.

2.1. Definition and overview of fundamental principles

A blockchain is a digital data structure, a shared and distributed database that contains a continuously expanding log of transactions and their chronological order. The data structure is in other words a ledger that may contain digital transactions, data records and executables. Transactions are aggregated into larger formations, called *blocks*, which are time-stamped and cryptographically linked to previous blocks forming a chain of records that determines the sequencing order of events or the ‘blockchain’. Apart from describing the data structure itself, the terminology is also broadly used in the literature to represent digital consensus architectures, algorithms or domains of applications built on top of such architectures [19].

Blockchains run on digital networks. Data transmission in such networks is equivalent to copying data from one place to the other, e.g. in the cryptocurrency domain this is equivalent to copying digital coins from one user's electronic wallet to another's. The principal challenge resides in the fact that the system needs to ensure that coins are only spent once and there is no double-spending. A traditional solution is to use a central point of authority, such as a central bank, who acts as the trusted intermediary between transacting parties and whose job is to store, safeguard the valid state of the ledger and keep the records up to date. If multiple parties need to write in the ledger at the same time, a central authority also implements concurrency control and consolidates changes in the ledger. In several occasions, central management may not be feasible or desirable, as it introduces intermediary costs and requires network users to trust a third party to operate the system [19]. Centralised systems also have significant disadvantages due to a single point of failure, which renders them more vulnerable to both technical failures and malicious attacks [32].

The primary purpose of blockchain technologies is to remove the need for such intermediaries and replace them with a distributed network of digital users who work in partnership to verify transactions and safeguard the integrity of the ledger. Contrary to centralised systems, every member of the blockchain network holds his own copy of the ledger or can access it in the open cloud (see also Fig. 1). As a result, anyone in the network can have access to the historic log of the system transactions and verify their validity, enabling a high level of transparency. If central management is removed, the challenge resides in finding an efficient way to consolidate and synchronise multiple copies of the ledger. The exact process of validation and ledger consolidation varies for different types of blockchains, however in principle, network members compare their versions of the ledger through a process intuitively akin to distributed voting [16], through which consensus on the valid state of the ledger is reached. These validation mechanisms are known as *distributed consensus algorithms* and are extensively described in Section 2.4. Collaboration and honest behaviour of distributed nodes is established by game-theoretic incentives or rewards [33]. In fact, blockchains can be very difficult to tamper with, without a significant part of the network colluding. Consequently, blockchain

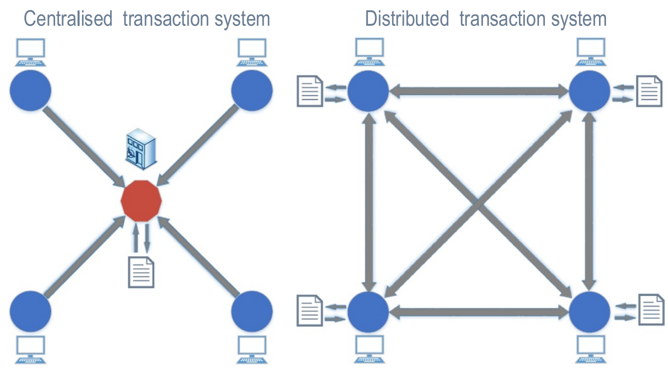

Fig. 1. Centralised and distributed transactional platforms: a single trusted authority manages the ledger as opposed to every member holding a copy of the ledger.

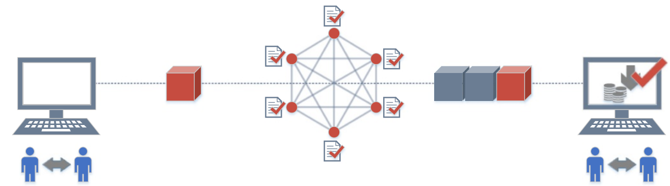

Fig. 2. Visual representation of a blockchain transaction: users agree on a transaction which is included in a block, its validity is confirmed by distributed nodes of the network and the block is added to the growing chain of blocks before transaction is confirmed and payments finalised.

systems can be secure and tamper-resistant.

Other elements that ensure enhanced security are hash functions and public-key cryptography. *Cryptographic hash functions* are mathematical algorithms or one-way functions that take an input and transform it into an output of specific length, e.g. a series of 256 bits, called the hash output. Their operation relies on the fact that it is extremely difficult to recreate the original input data from the hash output alone (collision resistance). In addition, blockchains use *public-key cryptography* [34], an asymmetric cryptography protocol. Each user holds two cryptographic keys consisted of numeric or alphanumeric characters, a secret private key and a public key, which can be shared with other users in the network. The keys are mathematically related in such a way that information encrypted by one part can only be decrypted by its counterpart. The use of public-private key cryptography ensures authentication, meaning that a transaction is initiated by the source it claims to be from, and authorisation, meaning that actions are performed by users who have the right to do so. For example, the network can verify the sender's identity, as only the sender's public key can decrypt the original message (encrypted and digitally signed by the sender's private key). A message processed with one's public key can only be decrypted by the intended recipient holding the secret private key. These and other standard communication features such as data validity and security are achieved in blockchain systems by use of P2P communication and advanced cryptographic techniques.

According to the UK Government Office for Science [11], the real potential of blockchain technologies can be fully realised only when combined with *smart contracts*, i.e. user-defined programs that determine the rules of writing in the ledger. Smart contracts are executable programs that make changes in the ledger and can be triggered automatically if a certain condition is met, such as if an agreement between the transacting parties is honoured [9]. Contract terms are recorded in computer language encoding legal constraints and terms of agreement. Smart contracts are self-enforceable and tamper-proof bringing about significant benefits such as removing the intermediaries [20] and reducing transacting, contracting, enforcement and compliance costs [11]. An additional benefit is that low-value transactions can be made cost-efficient, while blockchains can ensure interoperability between transaction systems [12].

To improve further understanding on the operation of blockchain systems, we introduce in the next section two significant operating blockchain systems, Bitcoin, the first known application of blockchains and Ethereum, a blockchain platform based on smart contracts.

2.2. Two important paradigms: Bitcoin and Ethereum

The world's first cryptocurrency, *Bitcoin*, was established in 2009 following the public release of a paper by Nakamoto [35], an author whose real identity remains unknown. He proposed a distributed electronic cash payment system that uses P2P communication of anonymous and unknown Internet users. Digital cash transacted between users is not issued or controlled by a central bank but by a network of computers that operate in collaboration and use cryptography to assure security [36]. While the idea initially faced widespread scepticism, Bitcoin has in the more recent years emerged from obscurity, its price having increased by over 1700% and trading around $20,000 at the end of 2017 [37].

Each user in the Bitcoin system holds a digital wallet, where coins are stored, a private and a public key. The wallet can only be accessed by the user's secret private key. The wallet's address or Bitcoin address is derived from a user's public key and it is used to identify a user, offering *pseudonymity*. From initialisation to finality, a Bitcoin transaction follows the subsequent procedure (a more detailed description can be found in [36]). Before a Bitcoin transaction is initiated, transacting parties need to know each others public addresses. The sender creates an outgoing transaction, if enough coins are stored in his wallet (see also Fig. 2 for a visual representation of a blockchain transaction). A transaction contains information on the amount of coins traded and the addresses of transacting parties. A transaction is encrypted with the receiver's public key, it is digitally signed by the sender and afterwards transmitted to the Bitcoin network. Special nodes aggregate all outgoing transactions in the last 10 min into a single block. These nodes are also responsible for fine-tuning the validation process so that on average one block would require approximately 10 min to be validated and included in the blockchain [38]. Next, validator nodes, broadly known as miners, start competing with each other to solve a cryptographic puzzle and earn the right to add the block in the existing ledger and receive a financial reward consisted of two parts: a bounty agreed by all network members (currently this stands at 12.5 Bitcoins every time a miner is successful) and transaction fees that are offered by transaction parties. The successful miner is selected by a random selection process based on the computational work required, broadly known as 'proof of work' [35] (a detailed description of 'proof of work' and other consensus strategies under development are presented in detail in Section 2.4). When a miner succeeds, the solution is transmitted to the network and other miners start working in the next block. Succeeding blocks contain the hash output of the newly validated block and its transactions. Users can be sure that a block is valid as it is computationally expensive to have been produced and is linked with previous blocks. On average one block is generated approximately every 10 min [35]. The process of validation is run in parallel by many miners, therefore a transaction might be included in two or more blocks leading to multiple chains that need to be consolidated. The resulting structure of the blockchain is a tree of blocks and consensus refers to the valid path of the tree from root (the genesis block) to the leaf (the block containing the most recent transactions) [39]. The solution to this issue is that the network keeps track of multiple chains, but eventually network members consider the longest chain formed or most computationally expensive, to represent the valid state of the ledger. Any changes in a single block would require renewed computational effort and proof of work for all succeeding blocks. As a result a computational minority is outpaced by the computational power of all other truthful miners [33], which makes Bitcoin very resilient to malicious attacks.

According to a technical report released by the European Commission [36], 'the major contribution of Bitcoin is the solution of how 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'. By achieving this, Bitcoin introduced the concept of *'cryptoeconomy'*. According to Babbitt and Dietz [40], 'cryptoeconomy is not defined by geographic location, political structure or legal system, but uses cryptographic techniques to constrain behaviour in place of using trusted third parties'. Most important, Bitcoin has opened a series of possibilities for blockchain-based innovative applications not only for financial transactions but also for transfer and trading of digital assets, aiming to guarantee safety, security and legitimacy.

While Bitcoin represents the largest and most established blockchain application up to date, Ethereum has dominated blockchain applications beside cryptocurrencies. *Ethereum* [41] is an innovative blockchain-based virtual machine and Cloud 2.0 platform that comes with an embedded programming language that allows users to create their own applications that run on top of blockchain architectures [42]. Ethereum enables user-created smart contracts and aims to build an all-purpose technology platform, on which transaction-based application concepts may be built [39]. According to a recent report by Eurelectric, the Union of the electricity industry, more than 1000 projects are currently using Ethereum [43]. Many startups are using Ethereum-based coins and cryptocurrencies for Initial Coin Offerings (ICOs), as a means to raise funding. A core application of Ethereum are smart contracts and Decentralised Applications (DApps). DApps are open-source, decentralised applications that can operate autonomously and without human intervention. DApps make use of cryptocurrencies or tokens, are executed in a network of computers and store outputs in public ledgers.

Applications like Bitcoin represent a completely distributed ecosystem, the integrity and security of which is expensive to maintain. Other applications may not need complete decentralisation, therefore various system architectures have been proposed. These solutions are reviewed in the following section.

2.3. Taxonomies of blockchain system architectures

A blockchain network or system can follow different rules and system architectures depending on desired operation and specific use case. Blockchain systems are typically consisted of network *users* and *validators*. User nodes can initiate or receive transactions and hold a copy of the ledger. In addition to read access privileges, validators are responsible for approving modifications of the ledger and reaching consensus throughout the network regarding the valid state of the ledger. Depending on the system configuration, partial or universal access rights and validations rights may apply. All Internet users can join a *public* blockchain system. On the contrary, with *private* blockchains the access is restricted only to authorised participants. *Permissionless* ledgers are completely distributed and censorship-resistant as any member of the network can contribute to the validation of transactions. On the contrary, with *permissioned* ledgers only certain validator nodes hold write access rights to modify the blockchain (see Fig. 3). With public and permissionless ledgers, users and validators are completely unknown to each other, therefore the collaborative effort and trust required for ledger management is induced by game-theoretic equilibria and rewards. The structure of incentives typically involves spending resources such as computational work, electricity or penalisation that aims to deter selfish behaviour [16]. With private and permissioned ledgers the users' identity is known similarly to know-your-customer practices (KYC). Validator nodes are known and trusted to behave honestly, therefore artificial incentives are not required to guarantee the system's operation. Consequently, private and permissioned ledgers can be faster, more flexible and efficient, however, this comes in expense of immutability and censorship-resistance [16]. In addition, some ledger architectures can be classified as *consortium* blockchains, i.e. hybrids that stand between public and private blockchains [44].

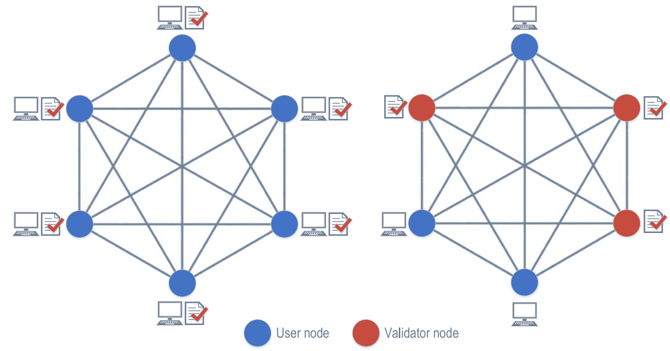

Fig. 3. Classification of blockchain architectures, public permissionless ledgers (any user can have join the network and validation process) and private permissioned ledgers (where network access and validation process is restricted to authorised nodes) - figure based on [45].

Blockchains can also be classified according to their development purpose, i.e. in *general purpose* or *specific purpose* blockchains. Typical examples are Ethereum, designed to accommodate a wide range of use cases and applications and Bitcoin, designed specifically for cryptocurrency transactions, respectively. In terms of governance and protocol rules of the system operation, blockchains can be classified as open-source or closed-source. *Open-source* architectures are open to all network members and can benefit from continuous and transparent peer review, public debate and community decision-making. *Closed-source* blockchains operate similarly to private enterprises, where any changes in the rules of the system operation are decided in private. It is important to understand that one blockchain solution architecture does not fit all applications and use cases, therefore hybrid approaches that lay anywhere in the spectrum between public and private blockchains and have various degrees of centralisation can be explored. The resulting system architecture and the consensus algorithm applied in the system environment are jointly responsible for key performance features, such as speed, scalability and efficiency of the resources spent. A review on different consensus algorithms is presented in the following section.

2.4. Distributed consensus algorithms

Existing literature describes many types of distributed consensus algorithms being developed, each providing distinctive features, advantages and disadvantages. The methodology used for reaching consensus in blockchain networks determines to a large extent key performance characteristics such as scalability, transaction speed, transaction finality, security and spending of resources such as electricity. Broadly speaking, every method requires a procedure for generating and subsequently accepting a block. A block can be generated or proposed by some node in the network, and it encodes a number of transactions (e.g. in a cryptocurrency system, these are monetary transactions between different accounts). Next, a key step is for the proposed block/corresponding transactions to be accepted by network members, a process called *reaching consensus*. Once a block is accepted, it becomes part of the blockchain, and newly generated blocks are cryptographically linked to it. After a time (depending on the consensus algorithm used), the block becomes a permanent part of the blockchain, i.e. it reaches *finality*. Note that finality does not exclude the existence of small statistical chance that the block is reversed, as part of a future fork, occurring either by design or as a result of an attack. However, this chance of reversal decreases with every new appended block, and for an established blockchain system, it becomes infinitesimally small.

Reaching consensus on which blocks/transactions to accept as valid in a distributed system is challenging. Consensus algorithms have to be resilient to failures of nodes, message delays and corrupt messages, as well as unreliable, unresponsive or even deliberately malicious nodes [46]. A large number of approaches for the consensus problem have been proposed. Some authors [47,48] broadly classify these as *lottery-based* and *voting-based* (although note that some of the more complex consensus approaches have elements that fit into both categories). Lottery-based approaches include proof of work (PoW) public blockchains (used by most cryptocurrency systems, such as Bitcoin or Ethereum). In PoW systems (reviewed in Section 2.4.1), the algorithm rewards participants who solve cryptographic puzzles in order to validate transactions and create new blocks. Another alternative are proof of stake systems (Section 2.4.2), in which validators are selected either at random or through a round robin mechanism, but crucially the weight of the 'vote' of each validator depends on the size of his 'stake' in the system - defined, for example, as the amount of cryptocurrency held in deposit or another commodity. Voting-based approaches to validation include those based on the Practical Byzantine Fault Tolerance (PBFT) algorithm. In Byzantine fault tolerance (described in Section 2.4.3), nodes transmit votes for blocks to accept in a multi-round process, at the end of which validators agree on whether to accept a block as a permanent part of the chain (finality). However, as votes are transmitted through a potentially unreliable network and some of the validators may be untrustworthy, the consensus voting process requires careful design.

Each of these methods presents trade-offs between a set of advantages/disadvantages. Methods that rely on random selection processes scale well to large dimensions. Good scalability means that a system performs well as it grows in scale, for example it can handle an increased number of transactions/blocks within a reasonable time frame and for an increased number of network users/nodes. However, these lottery-based systems may result in multiple chains at different nodes in the network that need to be consolidated and resolved before finality is reached. This can also affect the speed transactions are recorded in the blockchain. On the contrary, methods based on voting are faster to achieve finality, but may take longer to achieve consensus for a large number of nodes in the network, because nodes need to exchange messages with each other and voting may last for multiple rounds until agreement is reached. This results in a trade-off between scalability and finality/speed [47]. It is worth noting that efforts to improve scalability and speed of transactions are ongoing by the blockchain community. Several solutions have been proposed including sharding, sidechains and utilisation of payment channels. Sharding is a technique that uses a different subset of nodes from the pool of validators to verify each transaction. As along as a large enough set of validating nodes is used, security features can be preserved. This in theory could enable parallel processing in the verification of transactions and improve transaction speed, however the methodology is still under development [49]. A different technique is the use of sidechains [50] or second-layer chains [51]. Sidechains can be used to store the actual data related to transactions and are used to ease the burden of storing all information in the main chain. Speed can be compromised when transactions contain large amounts of data, as blocks have a limited size. To overcome this, main chains are used to store the proof of correctness of sidechains, rather than the actual data, hence acting as a control layer rather than as a complete data store [50]. Another solution proposed is the use of payment channels that act on a separate control layer than the blockchain itself [52]. Payment channels require multiple signatures that allow parties to transact with each other for an agreed period of time without the need to broadcast each transaction to the main blockchain network. Network members are not required to have established payment channels with all potential transacting parties, as payments can be sent via intermediary nodes with a process similar to Internet routing. Consequently, the majority of transactions are executed off-chain and only new or uncooperative channels are transmitted to the blockchain network. Similar solutions can be promising especially for the settlement of lower risks microtransactions or micropayments as they can significantly increase transaction capacity and reduce cost per transaction and transaction fees. However, they are still under development and need to prove several aspects related to security (such as denial of service attacks) and trust [49].

Validation and cooperation within the network often requires spending resources, such as computational power or coins. Honest behaviour of validating nodes is assured either by financial rewards or countermeasures that take some form of punishment. Rewards may include direct coin assignment or receiving substantial transaction fees. Punishment may include losing money, deposits. Either way, the incentives' mechanism design reflects a form of resources expenditure, which can be money, computational power, electricity, time, etc. Minimising resources or energy spent forms a significant criteria for evaluating blockchain performance. PoW algorithms for example are known to be energy intensive as they spent significant amounts of energy to validate transactions. While this is a significant concern and wastage of resources needs to be minimised, it is also crucial for not compromising blockchain system security. In fact, the design of validating mechanisms and incentives can determine system vulnerabilities to malicious behaviour, potential cyber-attacks or collusion. This results in a trade-off between security and waste of resources/cost. Some authors argue that incentives and rewards form an integral part of blockchain systems and are required to safeguard their security and integrity [53]. Other authors state that the essence of blockchains is purely informational and process-oriented [54] and see blockchain solutions as a technology that achieves consensus in P2P networks [55].

In addition, distributed consensus strategies are a direct consequence of the trust within the environment blockchain networks operate and their centralisation risks. For example, high cost strategies may be inevitable for public trustless blockchain applications such as Bitcoin, however they may be redundant for private blockchains operating in trusted environments. Applications of blockchain systems, such as in the corporate world, call for various requirements depending on specific cases. Several applications require real-time or near real-time transaction clearance and low latency. Other applications need to have good scalability. Traditional PoW approaches support open and censorship-resistant platforms, however they are not suitable for use cases that require immediate transaction finality or high transaction rates. On the other hand, consensus mechanisms developed for private blockchains may become inefficient when scaled to a large number of participants (Table 1 provides a summary of key characteristics). A detailed comparison of different algorithms can also be found in [15,44,46,47,56].

Next, we summarise the most important algorithms starting with Bitcoin's most widely used proof of work.

2.4.1. Proof of Work (PoW)

The origins of PoW, used by Bitcoin, can be found in the 'Hashcash' proof of work developed to limit denial of service attacks on Internet resources [57]. Validators or miners compete with each other to add a new block in the existing blockchain by solving a cryptographical puzzle of generating a hash output that starts with a number of consecutive zeros in the most significant positions. The method used adds a

Table 1
Summarised distributed consensus strategies and main characteristics based on [47].

Technical features	Permissioned lottery-based	Permissioned voting-based	Permissionless PoW
Scalability	Good	Moderate	Good
Speed	Good	Good	Poor
Finality	Moderate	Good	Poor

nonce, i.e. a random number that can only be used once, to the block, and calculates the hash output of the block header. The block header contains information such as the hash of the previous block validated and a special hash of all transactions contained in the block (Merkle tree). The goal for all miners is to achieve a hash output that is lower than a specified target. Miners have no way to predict or influence the outcome, so the only feasible action is that of trial and error. This brute-forcing procedure requires computational effort that increases exponentially with the number of trailing zeros. When a correct hash output is found, the block is returned to the Bitcoin network and is accepted by other nodes if all transactions are valid and unspent, and the successful miner takes a financial reward.

Other miners accept the newly generated block by starting work on the consecutive block. Crucially, all succeeding blocks contain hash outputs from all preceding blocks. As generation of hash outputs is random and performed in parallel by many miners, multiple chains may appear. In this occasion, the network stores all resulting chains. Network members eventually abandon all other chains but the longest, which is assumed to have been produced by a network majority of computational power and therefore to represent the most valid state of the ledger. As a result, malicious attackers are constantly outpaced by the honest part of the network, unless they can control more than 51% of the computational power in the network. In the case of a 51% attack, malicious nodes could potentially rewrite all history of transactions. Breaches in security can be introduced by users, miners, hackers or man-in-the-middle attacks (a detailed discussion of these issues is provided in [36]). Initially, Bitcoin mining relied on the computing power of standard computers, so anyone could become a miner. Since 2014 mining has been dominated by specially designed computer chips, known as application specific integrated circuits (ASICs) [58]. Miners have increasingly joined coalition pools in order to leverage risks and maximise returns. As a result, mining power is continuously becoming more centralized in cartels or 'mining pools'. This has generated a direction of research that uses techniques from game theory and mechanism design to discourage centralised cartels from forming and reduce their influence on the Bitcoin system [59].

PoW strategies have proved they can scale to a large number of users however transaction rates and finality may not be suitable for certain use cases [54]. For example, the original version of Bitcoin is able to process about 7 transactions per second [60] (1 MB block size and a few thousand transactions per block [61]), 1 block every 10 min and may require on average up to 1 h to achieve 'finality'. Note here that in practice confirmation time may vary as block generation is not deterministic. In reality, confirmation time depends on the amount of network activity and transaction fees. Nodes need to store multiple chains when they appear, however the older a block in the chain, the more unlikely it is for it to be reversed. A typical number of confirmations accepted by the majority of the Bitcoin community and wallet providers is 6 confirmations, i.e. it takes approximately 1 h for the block to get accepted [62]. Early blockchains developed in the Ethereum platform that use PoW can deal a maximum of 20 transactions per second [63]. Visa on the other hand is believed to be able to support 24,000 transactions per second (current average of 1700 transactions per second). Blockchain system developers are constantly working to improve speed and scalalability. Solutions to these issues are being explored such as increasing the block size [58] or pruning [35] but also utilisation of sharding, sidechains and payment channels that promise instant finality [52]. Such solutions have the potential to significantly improve transaction rates, however, this places greater onus on validators, which can lead to undesired centralisation [33].

A main criticism point is that PoW is responsible for wasting large amounts of real resources such as electricity. For example, Ethereum's Wiki pages claim that Bitcoin and Ethereum burn over $1 million worth of electricity and hardware costs per day for running their consensus mechanism [48]. Pilkington [54] cites a media release named the Bitcurrency calculator, which shows that Bitcoin could one day consume up to 60% of global electricity production, equivalent to 13,000 TWh powering 1.5 billion homes. Other sources report that Bitcoin could consume as much electricity as Denmark [64] by 2020, with validation of one single Bitcoin transaction currently consuming 200 kWh of electricity [65]. This cost may not be justified for low value or low-risk transactions where users can be trusted or there are established methods to prevent malicious behaviour [33]. To solve these issues alternative strategies have been proposed, such as proof of stake.

2.4.2. Proof of Stake (PoS)

Criticism to PoW led to an alternative algorithm being proposed broadly known as proof of stake (PoS). PoS replaces computational work with a random selection process, where the chance of successful mining with PoS is proportionally related to the wealth of validators. The probability of generating a block depends on what the stake nodes have invested in the system, i.e. coin ownership [56]. This approach can potentially result to faster blockchains [54] that have much lower electricity consumption and a decreased likelihood of a 51% attack [48]. In addition, there is no need to constantly generate new coins to incentivise validation. Instead, miners rewards are down only to transaction fees and cannot achieve greater gains by investing in hardware equipment, such as ASICs. PoS can make use of game-theoretical mechanism design to prevent collusions and centralisation, often penalising dishonest and malicious behaviour. The main vulnerability of PoS systems is known as the 'nothing at stake' problem or in other words that voting/claiming financial rewards for multiple chains is inexpensive. Several solutions have been proposed such as integrating a punishment mechanism for validators that simultaneously create blocks in multiple chains and automatically deducting coins owned or deposited. Another strategy is to punish validators for creating blocks on the wrong chain, intuitively similarly to PoW, where also validators incur the cost of electricity. Validating nodes are exposed to greater risks in the latter case, but on the other hand, these nodes are not required to be known ahead of time [48]. PoS-based algorithms come in great variety and can be used in public blockchains, where validators are unknown and untrustworthy, or in private/business-oriented settings, where validators form a known set of trusted entities [48]. Ethereum, the most popular blockchain platform for technology developers and enterprises is planning to move from PoW to PoS solutions. In trusted or semi-trusted environments voting-based algorithms such as Practical Byzantine Fault Tolerance (PBFT) can provide adequate solutions. PBFT is presented in the following section.

2.4.3. Practical Byzantine Fault Tolerance (PBFT)

Byzantine Fault Tolerance (BFT) algorithms have their origin in the work on Byzantine faults, first characterized by Lamport et al. in a seminal computer science paper [66]. Briefly described, the problem concerns a set of Byzantine generals (or nodes in a blockchain setting), agreeing on a joint plan of action. For the Byzantine generals, the joint action is coordinating the different parts of an army to attack a fortress simultaneously (in the case of blockchains, this corresponds to reaching consensus on whether to validate a block/set of transactions). The challenge is that messages between the generals have to pass inside enemy territory and may be lost without notification of either sender/receiver (i.e. travel in an unreliable, distributed network). Moreover, some of the generals may be traitors and interested in passing messages that sabotage the battle plan, by sending false or distorted messages, or not replying to messages at all. The challenge is, to ensure that loyal generals can reach consensus on the attack plan, and a small number of traitors should not cause them to adopt a bad plan. In the terminology of blockchains, a small number of unreliable or potentially malicious nodes should not be able to cause the validation of a bad block/set of transactions. The number of malicious nodes which can be safely tolerated varies, but Lamport et al. [66] show that guarantees can be provided if it is no more than 1/3 of the total number. The work of Castro and Liskov [67] proposed the first practical approach that allows for BFT applications with low overhead, which they called Practical Byzantine Fault Tolerance [67] (PBFT). The PBFT algorithm proposes the concept of primary and secondary replicas, where the secondary replicas check the correctness and liveliness (capacity to produce a response in a given time) of the primary and can switch to a new primary if the original one is compromised.

PBFT algorithms are a key building block of most modern blockchain systems using the voting-based consensus approach. Transactions are individually verified and signed by known validator nodes, making PBFT more suitable for use with trusted environments rather than public permissionless ledger applications. When a sufficient amount of signatures is collected, transactions are considered valid and consensus is reached. PBFT provides instant finality, as blocks that have been globally verified cannot be reversed. However, the algorithm requires at least 2/3 of the network to behave honestly and messages overhead may increase significantly as the size of the network increases, affecting both speed and scalability [46]. Many variants of BFT-based protocols have been proposed (see [60] for a detailed review) by key developers, such as Hyperledger, the open platform supported by the Linux Foundation [47] and Tendermint [68].

2.4.4. Delegated Proof of Stake (DPoS)

DPoS utilises distributed voting to elect delegates and witnesses that participate in the validation process. Every member votes to elect a number of witnesses to generate a block. Each witness is assigned a fixed schedule, e.g. every 2 s, to produce a block. The system relies on reputation and dishonest witnesses can be voted out of the system. This deterministic selection of block producers allows very fast confirmation times [69]. Similarly to witnesses, stakeholders elect delegates who are responsible for decisions on protocol rules and system parameters, such as transaction fees, block size, transactions per block etc. The algorithm is described as a shareholder voting consensus scheme, because every single member of the network can decide who can be trusted and validation power is not concentrated to the members with most resources [56], unlike PoS. DPoS is a promising technology that aims to achieve speed, high transaction rates and low energy consumption [56]. The main criticism points are centralisation risks caused by possible low participation of nodes in the voting/election process [70]. According to Bitshares, a DPoS consensus developer [69], DPoS can survive up to 49% Byzantine faults in a synchronous network model.

2.4.5. Federated Byzantine Agreement (FBA)

With FBA, participants rely on a small set of validators that each member considers trustworthy [71]. Members accept transactions that are previously accepted by their trusted validators. Ripple and Stellar are two protocols that use variations of the FBA model. With Ripple, consensus happens in multiple rounds. Users form a ‘candidate set’ of transactions and broadcast it to the network. Other nodes vote on the transactions and adjust their candidate set according to the majority of the votes. The process is repeated until the candidate set is finalised and receives more than 80% of the total votes. A similar variation is used by Stellar. A block is accepted if it is signed by a specific quorum of validators, defined as a sufficient set of nodes required to reach consensus.

2.4.6. Proof of Authority (PoAu)

Block generation with PoAu requires granting special permission to one or more members to make changes in the blockchain. For example, one member holding a special key may be responsible for generating all the blocks. Essentially, PoAu can be seen as a modified PoS algorithm, where validators' stake is their own identity. Network members put their trust into authorised nodes and a block is accepted if the majority of authorised nodes signs the block. Any new validators can be added to the system via voting [43]. Although the method represents a more centralised approach most appropriate for governing or regulatory bodies, it is currently also proving popular with utility companies in the energy sector. The consensus algorithm may be useful in special use cases where security and integrity cannot be put at risk [56]. An example is the Energy Web blockchain that can achieve confirmation time of 3–4 s and can scale to several thousand transactions per second [72].

2.4.7. Proof of Elapsed Time (PoET)

PoET was first proposed and developed by Intel's Sawtooth project [73]. The algorithm aims to develop a fair consensus algorithm that can scale to thousands of nodes and can be energy efficient. The algorithm aims to replicate a fair and random block generation process without spending valuable resources, such as coins, computational power or electricity. This is achieved by utilising new CPU instructions and a trusted execution environment [74]. Validator nodes request a waiting time from a trusted function in a general-purpose processor. The node with the shortest wait time produces the block. The environment checks if claiming leadership is legitimate as per allocated wait time. The main criticism regarding this approach is the requirement of the environment developed by Intel, meaning that trust is still required to a single authority [75].

2.4.8. Proof of Activity (PoAc)

PoAc is a hybrid protocol that combines proof of work and proof of stake. Block templates that are empty of transactions are generated by miners using a traditional PoW approach. Next, the block is validated by a group consisted of a random set chosen depending on their stake in the system. Block validation is finalised when signatures are collected from all validators in the group. If nodes are not available, a new group is selected. PoAc combines advantages and disadvantages of PoW and PoS, such as wasting of resources and issues with validators double-signing [56].

2.4.9. Proof of Burn (PoB)

PoB aims to replicate PoW cost for validation by charging validator nodes, who pay in coins to earn the privilege of validating blocks. Validator nodes commit coins that are ‘burned’ and cannot be reclaimed to increase the chance of being selected by the random selection process. Validation depends on the willingness to waste money, as a result PoB results in unnecessary wastage of resources. On the other hand, centralisation risks do not depend on hardware equipment [56] unlike PoW.

2.4.10. Proof of Capacity (PoC)

PoC and other variants known as proof of space or proof of storage require that validator nodes to commit hard drive space to increase their chances of producing the next block and earn its reward. PoC generates large datasets known as ‘plots’ that occupy storage space. PoC can result in significant energy savings and does not rely on investment in expensive ASIC hardware. The method however, needs to address similar issues to the ‘nothing at stake’ problem [56]. An example network is the Pylon-Core developed by Pylon Networks, a Spanish startup, that can achieve a throughput rate of 7000 transactions per second [76].

2.5. Criteria for technology suitability

Blockchain technologies and distributed consensus strategies presented in previous sections demonstrate significant advantages, increased security, censorship resistance and transparency that might be useful for a variety of applications and use cases [16]. When considering the application of blockchain techniques to a new area of application a natural question arises whether blockchains are the right technology to address the challenges of the application. The emergent blockchain technology is still in its early days of development, therefore identification of suitable and promising use cases may be challenging. Several works [55,77] have attempted to address these challenges by analysing the criteria a use case needs to meet to be considered a good candidate for blockchain innovation. Summarising the findings of

[55,77], blockchains aim to deal with transaction payments for assets transferred or services provided. As a result, the first criteria to be met is that these assets can be represented in the form of a digital ledger or a database. Secondly, this database would need to be shared between different users and edits in the database need to be performed by multiple parties concurrently, meaning that resulting transactions are interdependent on other users' decisions. Network members are either unknown or cannot be trusted. Finally, a crucial question to ask is why decentralisation is required for a particular use case. Potential reasons for decentralisation can be reducing the costs introduced by intermediaries, achieving faster and secure transactions, automated clearance procedures, censorship-resistance, improved resilience to faults, the need to comply to transparency and regulation, and the elimination of the need of relying on a trusted intermediary. (For example, the vision behind Bitcoin and other cryptocurrencies was to eliminate the need of banks as trusted intermediary). Additionally, in such a decentralised environment, blockchains have the ability to assure traceability of transactions (both monetary or energy transactions), and hence achieve a level of transparency and trust in the ledger.

By applying these criteria, one can identify potential use cases for blockchains in the energy sector. The following sections are dedicated to potential use cases in the energy industry.

3. Blockchain potential and notable use cases in energy applications

Energy sector decision-makers [18] and utility companies [78] have asserted that blockchains could possibly offer solutions to challenges in the energy industry. The German Energy Agency [18] claims that blockchain technologies have the potential to improve the efficiency of current energy practices and processes, can accelerate the development of IoT platforms and digital applications and can provide innovation in P2P energy trading and decentralised generation. In addition, they report that blockchain technologies have the potential to significantly improve *current practices* of energy enterprises and utility companies by improving internal processes, customer services and costs [18].

Energy systems are undergoing a transformational change triggered by the advancement of distributed energy resources and information & communication technologies (ICT). One of the main challenges is the emerging decentralisation and digitalisation of the energy system, which requires the consideration, exploration and adoption of novel paradigms and distributed technologies. Due to their inherent nature blockchains could provide a promising solution to control and manage increasingly decentralised complex energy systems and microgrids [15,79,80]. Integrating small-scale renewables, distributed generation, flexibility services and consumer participation in the energy market is a demanding task. Some authors [79] argue that blockchains could provide innovative trading platforms where prosumers and consumers can trade interchangeably their energy surplus or flexible demand on a P2P basis. Active consumer participation can be secured and recorded into immutable, transparent and tamper-proof smart contracts. Enabling such automated trading platforms could be an efficient way of delivering price signals and information on energy costs to consumers [80], simultaneously providing them with incentives for demand response and smart management of their energy needs. Blockchains can enable local energy and consumer-oriented marketplaces or microgrids that aim to support local power generation and consumption [29]. One of the major benefits from this approach is reducing transmission losses and deferring expensive network upgrades. On the other hand, energy is still delivered through the physical grid, demand and supply need to carefully be managed and controlled to comply with real technical constraints and power system stability. According to a recently published report by Eurelectric [43], the physical exchange of electricity has so far inhibited larger adoption of blockchains in the energy sector, as opposed to applications in the finance sector. Blockchains can securely record ownership and origins of the energy consumed or supplied. As a result, blockchain solutions could be utilised for smart charging arrangements and sharing of resources, e.g. community storage or microgrids, but also for applications of data storage in smart grids and cybersecurity [81,82]. A key challenge as volumes of RES continue to increase is maintaining the security of supply and improving network resilience. By facilitating and accelerating IoT applications and enabling more efficient flexibility markets, blockchains could improve network resilience and security of supply [79]. A report by the Research Institute of the Finnish economy [16] argues that blockchains could assure interoperability in smart grid and IoT applications by offering open and transparent solutions. According to Deloitte [20], energy market operations could become more transparent and efficient. As a result, this could improve competition and facilitate consumer mobility and switching of energy suppliers. If cost savings opportunities are realised, we could leverage the technology to improve on fuel poverty and energy affordability issues.

By virtue of advantages offered, blockchains could potentially provide solutions across the energy trilemma: they could reduce *costs* by optimising energy processes, improve energy *security* in terms of cybersecurity, but also act as a supporting technology that could improve security of supply, and finally promote *sustainability* by facilitating renewable generation and low-carbon solutions. In the following sections, we discuss notable use cases proposed in the literature where blockchains could offer significant gains.

3.1. Blockchain potential impact on energy company operations

Blockchain technologies could be applied to a variety of use cases related to the operations and business processes of energy companies. Existing literature dictates potential applications and aspects of business models that might be affected, as summarised below:

- *Billing*: Blockchains, smart contracts and smart metering can realise automated billing for consumers and distributed generators [83]. Utility companies might benefit from the potential for energy micropayments, pay-as-you-go solutions or payment platforms for prepaid meters [84].
- *Sales and marketing*: Sales practices may change according to consumers' energy profile, individual preferences and environmental concerns [18]. Blockchains, in combination with artificial intelligence (AI) techniques such as machine learning (ML), can identify consumer energy patterns and therefore enable tailored and value added energy products provision.
- *Trading and markets*: Blockchain-enabled distributed trading platforms might disrupt market operations such as wholesale market management [18,20,83], commodity trading transactions [84] and risk management. Blockchains systems are currently being developed also for green certificates trading [84].
- *Automation*: Blockchains could improve control of decentralised energy systems and microgrids [18]. Adoption of local energy marketplaces enabled by localised P2P energy trading or distributed platforms can significantly increase energy self-production and self-consumption, also known as behind the meter activities [83], which can potentially affect revenues and tariffs.
- *Smart grid applications and data transfer*: Blockchains can potentially be used for communication of smart devices, data transmission or storage [18]. Intelligent devices in the smart grid include smart meters, advanced sensors, network monitoring equipment, control and energy management systems, but also smart home energy controllers and building monitoring systems. In addition to providing secure data transfer, smart grid applications can further benefit from data standardisation enabled by blockchain technology.
- *Grid management:* Blockchains could assist in network management of decentralised networks, flexibility services or asset management. Blockchains could achieve integrated flexibility trading platforms

and optimise flexible resources, which might otherwise lead to expensive network upgrades. As a result, blockchains might also affect revenues and tariffs for network use [83].

- *Security and identity management:* Protection of transactions and security can benefit from cryptographic techniques. Blockchain could safeguard privacy, data confidentiality [18] and identity management [84].
- *Sharing of resources:* Blockchains could offer charging solutions for sharing resources between multiple users, such as sharing EV charging infrastructure [84], data or common centralised community storage.
- *Competition:* Smart contracts could potentially simplify and speed up switching of energy suppliers [18,85]. Enhanced mobility in the market could increase competition and potentially reduce energy tariffs.
- *Transparency:* Immutable records and transparent processes can significantly improve auditing and regulatory compliance [84].

Blockchains can enable and potentially disrupt established business models and traditional roles of energy utility companies as discussed in [18,83,84,43] and shown above. The following sections elaborate on notable use cases presented in the literature.

3.2. Wholesale energy trading and supply

A potential application is utilising distributed ledger technologies in wholesale autonomous trading procedures. Wholesale energy markets consist of complex procedures that require third-party intermediaries such as brokers, trading agents, exchanges, price reporters, logistic providers, banks and regulators. Fig. 4 summarises the key entities and activities involved in a financial trade between two companies. Current procedures involve manual post-processing and increased communications to consolidate information held separately by each part of the transaction. As a result, current procedures are slow and time-consuming, as transactions need to be verified and reconciled multiple times from initialisation to final settlement [86]. Low speed of transactions and exchanges leads to frictional costs that are prohibitive to small-scale and distributed generators that are in practice excluded by the market.

Distributed ledger technologies and smart contracts can allow a generating unit to directly trade with a consumer or an energy retail supplier via autonomous trading agents cutting out the middle-man [20]. The agent would search for the best deal in the marketplace that satisfies a consumer's forecast demand for a given time period. The agreement would be safely recorded in the blockchain and automatically executed at the specified time of delivery. Payments would occur automatically at time of delivery as specified in agreed contract. Transaction data would be available to all parties and the system operator through a single point of access, the distributed ledger [20]. Similar use cases would require fundamental changes in the regulatory framework with potential serious effects on the role of mediators, such as brokers, exchanges and trading agencies.

The potential of blockchain for wholesale energy trading has been highlighted in a number of sources, with some consultancy reports [21] even arguing that it has the potential to transform the current energy market structure (shown in Fig. 5). However, realising this vision in practice will need to overcome a number of significant roadblock and technical challenges.

First the number of transactions that can be cleared using blockchains is often an order of magnitude smaller than what is possible

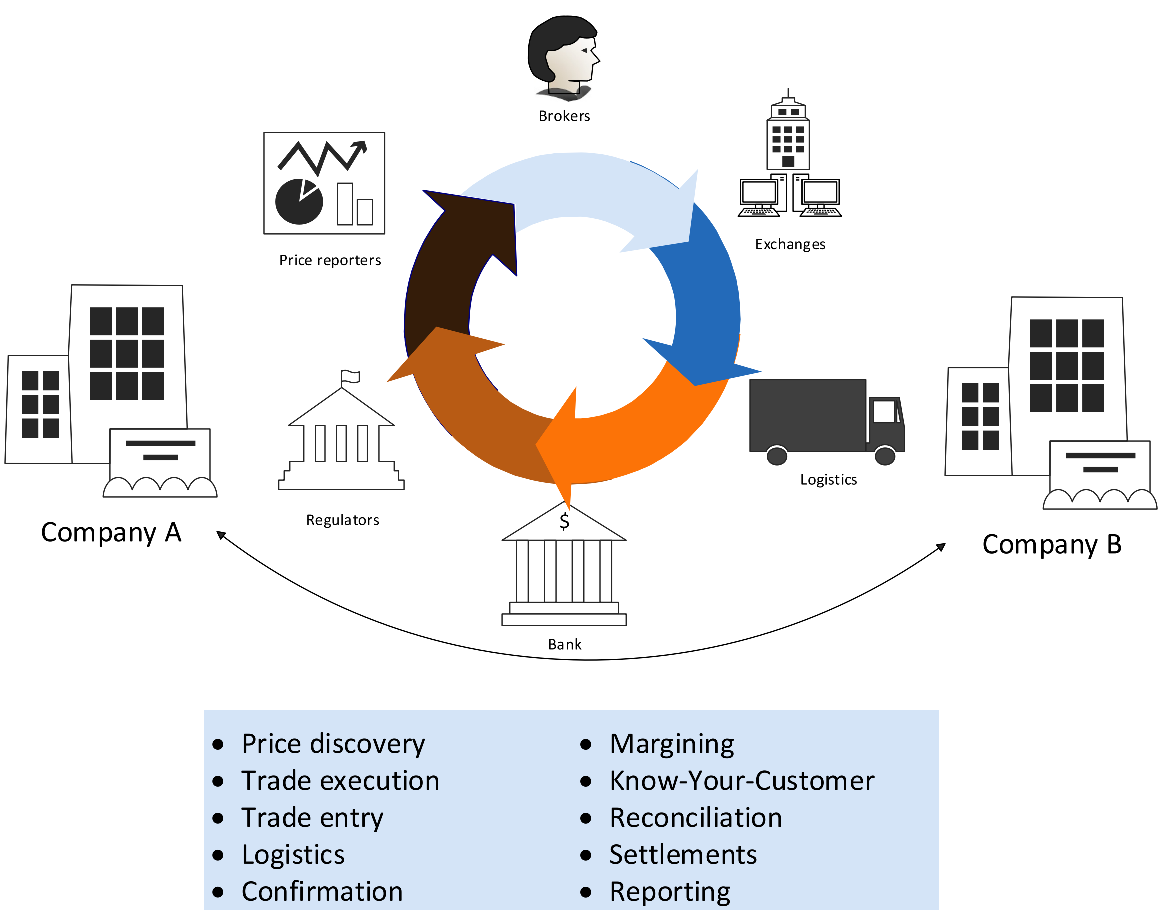

Fig. 4. Processes and third parties involved in typical energy commodities transactions as analysed in [86].

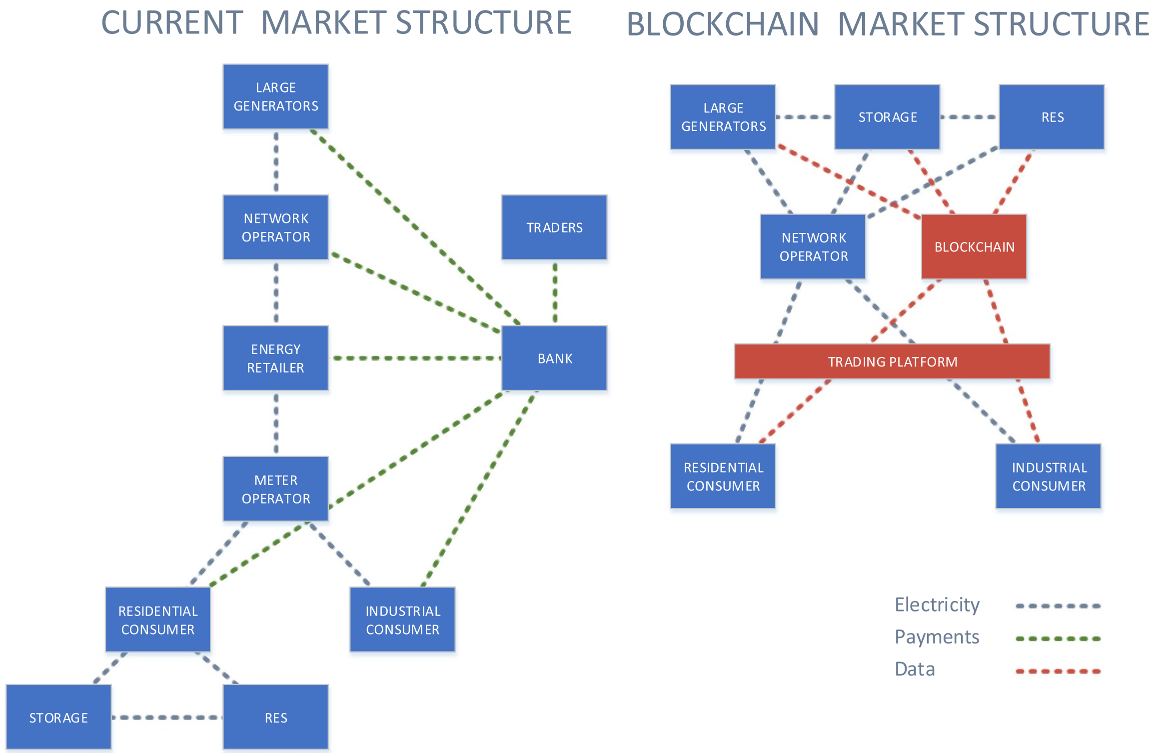

Fig. 5. Transformation of market with blockchains according to PWC [21].

through conventional electronic payments, especially those using proof of work algorithms to reach consensus. For example, Bitcoin network (the largest blockchain-enabled cryptocurrency) can clear in the order of up to tens of transactions per second (see Section 2.4.1), rather than the thousands or more transactions/second that the electronic payment systems used in banking clears every day. PoS and Byzantine fault tolerance systems (such as Ethereum or Tendermint) can provide a potential solution to this, yet implementing such solutions can present a significant overhead, and requires careful design and implementation.

Second, we believe it will be challenging to radically transform existing energy market structures in a short period of time. For this reason, many existing blockchain projects currently running have typically focused on only one part of the whole energy market, which is identified as most easily amenable to blockchain implementation, such as imbalance settlement (discussed in Section 3.3).

3.3. Imbalance settlement

An application of blockchains that has received significant attention is the settlement of imbalances in power markets. According to Elexon, the UK wholesale electricity market operator, imbalances can take from a few months up to 28 months to finalise [87]. The main reasons for delays experienced are lengthy processes of reconciliation, volume actualisations and confirmations [20]. Blockchains could undercut costs and time-delays by bringing back-office processes to a minimum. Electricity generated and consumed can be traced and recorded in open and transparent ledgers that can accelerate payments for services provided. DLT solutions would require integrating metering devices with blockchains, which might come with significant costs. According to [20], stakeholders could reduce credit risks and collateral requirements. In addition, the market operation itself would be more transparent and efficient with near real time confirmations. The blockchain-enabled platform would facilitate trading between different parties, improve auditability and process integrity, reduce the risk of malevolent behaviour (by providing secure data storing) and enable interoperability by standardising data formats across multiple organisations [20].

Moreover, in the context of imbalance settlement, the use of blockchain-enabled smart contracts should, in principle, allow exact tracking of which generator and consumer generated an imbalance, allowing for real-time billing. However, while several utilities and companies have begun to explore the use of blockchain for imbalance settlement, the issues of latency and low throughput (i.e. transactions processed per second) are still challenges that need to be addressed. Another issue is that ex-post balancing payments act more as an accounting tool of energy already generated or consumed, they do not incentivise real-time behaviour change (e.g. consumers do not receive a real-time signal to consume less when there is more renewable generation, i.e. adjust their demand to follow supply, one of the key aims of the ‘smart grid’ vision).

3.4. Digitalisation and IoT platforms

Promising applications for blockchain technologies can also be identified in the emerging fields of IoT platforms and the development of ICT such as in smart homes [88]. Blockchains facilitate digital P2P transactions, therefore can potentially enable machine-to-machine (M2M) communication and data exchanges between smart devices. An increasing number of smart devices (20.8 billion) could be connected on the Internet by 2020 [18]. In the energy space, smart meters and ICT equipment are increasingly being adopted in power systems [89]. The number of smart meter readings alone is expected to rise from 24 million a year to 220 million per day for a large utility company [90]. This trend combined with the power of automation and big data analytics can potentially transform the value chain in the energy sector. Useful insights from data can enhance power system performance and asset diagnostics which can lead to cost reduction. For electric utilities digitalisation offers an opportunity to improve network efficiency, billing processes, supply chain and enables exploration of new sources of innovation and novel business models [18]. Utilisation of data could lead to optimisation of demand aggregation services and demand response, could facilitate Virtual Power Plants (VPPs) and potentially enhance active consumer participation and renewable integration [90]. Digitalisation could lower management costs of smaller scale RES generators by remote maintenance and control enabled by intelligent integration of hardware, software, sensors, data, analytics and cloud connectivity [19]. The vision of the so-called smart grid [23,24] will see smart appliances, automated control of heating, ventilation and air conditioning (HVAC) units, adoption of EVs and the rise of self-generating prosumers. The smart grid vision states that interconnected smart devices will be able to coordinate and react to price, renewable availability or grid stability signals by adjusting accordingly their power consumption. Traditional centralised approaches become inefficient when scaled to a large number of devices that produce high volumes of data at high frequency. Local decision-making and distributed control can reduce the need for computational resources required to optimally operate future power systems. Blockchain applications could facilitate IoT platforms while open-source, shared and collaborative blockchain platforms can ensure interoperability in IoT applications [16].

An example based on an exercise of a blockchain-enabled IoT platform is presented by Mattila et al. [19], who visualise a local autonomous marketplace of a housing society with rooftop PVs, smart and flexible appliances, EVs, a battery energy system and smart meters that can measure bi-directional electricity flows (see Fig. 6). Blockchains can distinguish the electricity produced by each device enabling electricity trading between different machines. Based on user preferences and willingness to pay, autonomous trading agents forming an integral part of all smart devices, can decide optimal bidding strategies to trade energy through the platform. These devices can be programmed to operate in such way that desired objectives can be achieved, such as increasing energy self-sufficiency or minimising energy purchase from the main grid. Bids and offers made by each device are recorded in tamper-proof reliable ledgers. The authors argue that private blockchains that restrict access to the residents of the housing society would be most suitable for this application. The main grid could also participate in the marketplace for example by offering its spot prices. Smart devices need to combine data from the distributed marketplace with traded flows of electricity. They also need to have the capability to connect to each other. Devices would need to have some computational functionality, such as Raspberry Pi and a Linux-based operating system and data storage capability to locally store the ledger.

While this is a promising area for applying blockchains, there are a number of considerable challenges that need to be addressed. First, this vision requires the development of blockchain-enabled power electronics that are able to measure the demand of each device (fridge, washing machine, EV etc.) and interact with the blockchain system with low latency and delay. Even assuming these can be developed (and

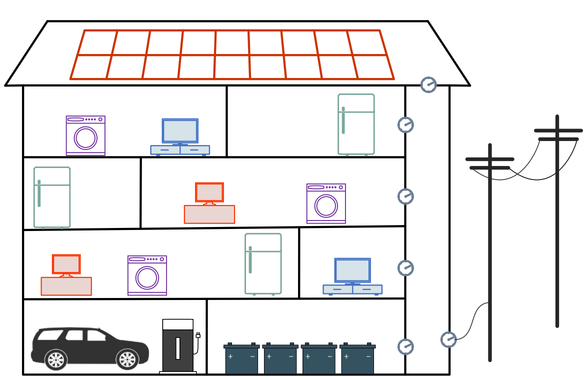

Fig. 6. Housing society electricity trading platform described in [19]: PV panels, smart appliances, EVs and local energy storage devices trade on a P2P fashion and adapt their consumption to achieve desired objectives such as minimising electricity costs, reducing grid imports or match demand to local RES supply.

indeed a number of projects have exactly this aim), there could be considerable consumer resistance especially due to *privacy* concerns. Despite the potential for monetary savings, it is unclear whether a consumer would want its consumption from e.g. electric shower, washing machine or EV to be publicly recorded in a public ledger. Hence, the way the information is recorded in the ledger, such as to preserve privacy and anonymity of individual domestic and industrial consumers could prove to be a key issue in blockchain implementations of IoT systems.

3.5. P2P trading and decentralised energy

Potential use cases in this category are decentralised trading in microgrids, bilateral transactions between prosumers and consumers and business-to-business (B2B) energy trading. According to energy system stakeholder views [18], blockchain could also provide solutions in demand response services, coordination of VPPs, grid and network management and control, management of energy storage systems, control of decentralised energy systems, community energy projects and coordination of RES power plant portfolio.

Peer-to-peer trading can be seen as a truly decentralised form of an energy market. This contrasts with applications such as imbalance settlement (described in Section 3.2), applications which still largely follow the existing structures of power markets.

This is an application domain where blockchain-enabled systems would fit most naturally, by enabling direct energy trading between energy consumers (energy producers/prosumers and end-consumers), who can use this approach to take control of their generation and demand. While this can usually be achieved in small communities and microgrids, a key question is how this fits with existing distribution network control and operation. Ultimately, the system operator companies (such as the National Grid and DSOs in the UK) control the grid infrastructure and have responsibility of power delivery. Hence, even in a truly decentralised energy market, they are expected to play a key role, although blockchains can potentially improve other aspects such as system operations.

3.5.1. Microgrids and consumer-centred marketplaces

Local and community energy projects and microgrids are expected to play an increasingly important role in energy systems. According to Berka and Creamer [91] locally-owned energy projects have a great potential to deliver socio-economic and environmental benefits for the communities involved. In microgrids, distributed generators, storage devices, uncontrollable and controllable loads form an interconnected system that can operate in synchronisation to the main grid or in complete autonomy, if operating in island-mode [92]. From a control point of view, microgrids act as a single system that has distinctive electric boundaries with respect to the main grid [93]. In addition to the formal definition, virtual microgrids can also be considered that can provide aggregate control of supply and demand outside electrical and physical boundaries. Microgrids promote localised energy production and consumption, which may lead to significant distribution and transmission losses reduction [94]. When coupled with sustainable resources, microgrids can enhance further integration of RES [95]. Local microgrids can improve network resilience, provide ancillary services, such as frequency and voltage support, to aging power systems with the potential to defer expensive network upgrade investment. In addition, they can provide energy services to consumers in the case of grid contingencies.

Efficient microgrid operation on a technical level, such as optimal control strategies and system architectures, has been extensively studied [96–102]. Trading in microgrid environments at a local level has also been proposed by several researchers that utilise autonomous agents such as in [103] where a flexible market for coordination of self-interested energy users, suppliers and utilities in a smart grid framework is presented. In [104] security of supply issues and limited network capacity is taken into account. In [105], a market mechanism allocates electricity and heat in microgrids with CHP. Other autonomous marketplaces for energy trading paradigms in the wholesale market have been developed by the AI community [106] (TADA) and [107] (POWER TAC). Local and decentralised energy systems need to overcome significant barriers, such as accounting for a large number of independent and self-interested actors, how to record the energy produced and consumed at different points in the microgrid, but also the issue of coordination between multiple sources and the central energy system so that demand and supply are balanced at all times [15]. An additional challenge that local or community-based energy systems need to overcome is related to social acceptance [108].

In terms of academic research, blockchains in energy markets form a new research area that has just started to be explored. One of the first works to consider the use of cryptocurrencies for P2P energy trading is the work by Mihaylov et al. [109]. Energy injected in to the grid is transformed to a virtual currency (NRGcoins) that enables local energy trading of prosumers. The rate coins are produced depends on the supply-demand conditions on the time of injection, so that real cost of energy is reflected in the price. Coins can be traded in exchange markets or buy electricity from the grid. Akasiadis and Chalkiadakis [110] present a cryptocurrency mechanism that is adopted to achieve demand shifting by prosumer coalitions. Local marketplaces rely increasingly on prosumers [28] and consumer participation and engagement [29]. Energy trading for microgrids in the developing world is discussed in [77]. In this work, solar battery units form the validating nodes of the blockchain network. The distributed consensus algorithm considered is proof of stake. A preliminary discussion on the use of blockchains in microgrids can also be found in [15]. Mylrea and Gupta [79] focus on technical characteristics (security, scalability and speed) of blockchains for distributed energy resources (DER) transaction exchanges and enhanced resilience. Apart from electricity, research work by Al Kawasmi et al. proposed a local market model to trade carbon emissions [111]. Trading of green certificates is discussed in [112].

Blockchains in local energy markets can incentivise end-consumer participation [80]. As a result, consumers are exposed to the real cost of energy, which might result in more rational energy consumption or suitable price signals for demand response [113]. Self-generating prosumers that have invested in PVs, small wind turbines or CHPs can participate in local energy markets. Until now, prosumers have not had real access to the energy market, which remains a privileged playing field for the institutionalised energy suppliers [11] due to high associated costs. Incentives for further RES investment, such as FiTs or export fees for selling energy surplus back to the grid are often inadequate or being removed [114]. Utility companies purchase this surplus at low prices and sell it back to other consumers at standard tariff prices. If prosumers are allowed to sell their surplus directly to other consumers without intermediaries, a potential for energy cost savings emerges for all stakeholders. Prosumers can derive greater benefits from their investment, as profits and value remains within the microgrid and local community. P2P trading in local energy marketplaces can provide socio-economic incentives that promote local renewable generation and therefore might form an alternative incentive for prospective prosumers [80]. Consumers, who cannot afford investing in renewable generation, either due to capital funding or limited space, can buy certified green energy at affordable prices. Emerging platforms indicate that there might be a market for matching consumers to renewable energy suppliers, such as in the case of Piclo and others (see [115] for a detailed review). Often consumers are willing to pay a premium for buying green energy, however currently there is no guarantee about the origin of energy purchased and most likely the energy used by end consumer is still sourced by the closest fossil-fuel power plant [116,117]. Current matching platform solutions are intermediaries that act as market access points for RES generating units and demand service providers, however traceability of energy flows is not currently possible. Blockchains on the other hand promise complete transparency on the origins of the energy purchased, such as its type, generating unit and exact location produced [18]. Community energy microgrids based on blockchains essentially enable localised energy trading between consumers, which is recorded in a secure and tamper-proof way. This has been the business model for startups like Powerledger and LO3 Energy. In the next section, we discuss in more detail the case study of the Brooklyn MicroGrid developed by LO3 Energy.

An important question in this context is the role to be played by the transmission and distribution system operators (TSOs/DSOs) and the Independent System Operators (ISOs). These players own the physical infrastructure of electricity grids and are responsible for system stability. System operator recoup their costs through system maintenance fees, but are also responsible for assuring that the decentralised energy trades agreed between parties can actually take place, given the physical system constraints.

Hence, TSOs/DSOs will have a key role to play in any blockchain implementation. We see their use of blockchains as twofold: First they can use blockchains to record more precise use of their network, hence allowing exact collecting of network fees corresponding to each energy transaction. In the case of local energy marketplaces, tariffs or prices set in P2P transactions need to account for grid charges, if the energy is transmitted through the public grid. Second, they can use the information about the peer-peer transactions recorded on the blockchains to better manage the capacity and power flows on their network. This, of course, would require new systems for managing the system that are able to use this information recorded on the blockchain in close to real-time, a challenging area requiring further research going forward. In fact, if connected to the main grid, all system users need to collaborate with the system operators and provide forecasts of energy demand and supply.

3.5.2. Example case study: the Brooklyn MicroGrid

Brooklyn MicroGrid is a blockchain-based P2P energy trading platform run by Transactive Grid, a partnership between LO3 Energy, Consensys, Siemens and Centrica. The microgrid is located in the Gowanus and Park Slope communities in Brooklyn, New York, and has completed a three month trial run of P2P energy trading between community members. A thorough analysis on the operation of this case study can be found in [80]. In summary, prosumers can sell their energy surplus directly to their neighbours by use of Ethereum-based smart contracts and PBFT consensus, implemented by Tendermint. The first trial included 5 prosumers and 5 neighbouring consumers and resulted in the first ever energy transaction recorded in blockchains worldwide. Energy surplus is measured by specially designed smart meters that can handle physical energy measurements and data, and sequentially transformed in equivalent energy tokens that can be traded in the local marketplace. Tokens indicate that a certain amount of energy was produced from the solar panels and can be transferred from a prosumer's smart meter wallet to end-consumers by use of blockchain technology. Tokens are deleted by the consumer's smart metering device, as purchased energy is used in the house. Microgrid users interact with the platform by specifying their individual price preferences in the form of willingness to pay or sell electricity. The platform can display location-specific and real-time energy prices. In the initial phase of the project, users manually trigger an agreement in the platform, whose terms are recorded in the blockchain. The ledger records contract terms, transacting parties, volumes of energy injected and consumed as measured by metering devices and crucially the chronological order of transactions. In addition, payments are automatically initiated by self-executed contracts. Every member of the community can have access to all historic transactions in the ledger and verify transactions for themselves.

More than 300 houses and small businesses, including around 50 PV prosumers and one small wind turbine generator, have signed for the next phase of development, which aims to achieve fully automated transactions [118]. Microgrid members will be able in the future not only to decide from whom to buy/sell energy tokens based on their price preferences, but also on other criteria that reflect their environmental or social values. For instance, a consumer can specify the maximum price he is willing to spend on locally produced renewable energy but he can also declare other preferences such as percentage of energy they are willing to purchase from local renewable energy or the main grid. Users can even prioritise selling/buying energy from friends, family or a specific neighbour [80]. The market clearance mechanism planned in the future is similar to how stock markets work. The platform will record the interest of buyers and sellers (bids/offers) in a order book. Users will be able to change their price preferences in real time. Locally produced energy will be first allocated to the highest bidders. The lowest allocated bid represents the market clearing price for each time slot, currently set 15 min intervals. Users will be able in the future to collect historic information on prices, and therefore learn and adapt their bidding strategies [80].

The Brooklyn MicroGrid project aims to serve as a testbed for exploring novel business models that promote consumer engagement in community projects. Localised energy trading opens up the potential for energy cost savings, however numerous research questions are open for debate. First and foremost, the importance and size of local energy trading markets needs to be investigated. Only by implementing large scale projects that represent diverse conditions in energy markets and social groups, will we determine willingness of consumers to participate in similar market architectures. Pricing in customer-sided markets are determined by the laws of demand and supply, resulting potentially in significant price volatility or even higher tariffs than the ones offered by the main grid. As a result, further work in engagement with and protection of the elderly, socially disadvantaged and vulnerable from price volatility is required. In addition, equilibrium prices will not only derived by simple cost functions but by social values and behaviour. As a result, individual preferences and social behaviour of market participants require further investigation in order to develop efficient market designs and pricing mechanisms. Other open research questions include the determination of most appropriate time frame for market clearance and data updates, which is increasingly dependent on the operating protocol rules and consensus.

Another crucial issue is that of balancing demand to supply. Currently, existing network infrastructure is used not only to distribute and supply the energy traded in the marketplace, but also to resolve issues caused by RES intermittency and load balancing. In the future, the project aims to explore how blockchain could be used for active management of the distribution network. In principle, energy produced by local prosumers can provide additional flexibility for local substation balancing [79].

This is currently not realised in the Brooklyn microgrid case, although a number of projects have begun exploring the use of techniques from artificial intelligence, machine learning and big data analytics to achieve demand-side flexibility. What blockchains could contribute these solutions (see also the P2P case discussed in Section 3.5) is the potential for decentralised matching between prosumers, enabling them to take real-time control of the own energy generation and supply.

According to Park and Yong [115], a technical challenge of P2P electricity trading systems from a grid's management perspective is that every node needs to respond to grid conditions, prices, local supply and demand. This means that individual consumers could be required to provide demand forecasts for use by the system operator, similarly to current electricity market operations. Machine learning techniques can be used to predict future behaviour of large sets of prosumers and electricity consumers [119]. Mylrea and Gourisetti [79] argue that aggregation of multiple blockchain users to comply with grid reliability requirements forms a technical challenge, as it might increase uncertainty and costs of balancing services. Distributed storage systems deployment and the adoption of EVs might help overcome these challenges. In addition, if energy systems evolve to being more local and decentralised, traditional roles of incumbents in the energy system, such as energy retailers or grid operators, might seriously be disrupted. Increasing energy self-sufficiency could bring reduced revenues, while at the same time costs related to the operation and maintenance of the power grid could increase, as grid asset utilisation deteriorates. This issue needs to be addressed along with fairer and more transparent allocation of distribution network charges to consumers, an important issue that can be ethically and politically complex to resolve.

In the following section we provide a systematic review of research and development projects utilising blockchain technologies in the energy space, and aims to provide insights into business models and research directions the blockchain community is focusing on, in this early stage of DLT adoption.

4. Blockchains in the energy industry: a systematic study

Industry stakeholders, utility companies and energy decision-makers have taken great interest in blockchain technologies. In this section, we provide a general overview on current use of blockchains in the energy industry, trials, pilot projects and novel business models that have emerged from the use of the technology. During our investigation we have identified more than 140 blockchain innovation projects and research initiatives in the energy space. The summarised results of our study and research projects involved are analytically presented in the Appendix A. We formally classify blockchain use cases into eight larger groups according to their purpose and field of activity: 1) metering/billing and security; 2) cryptocurrencies, tokens and investment; 3) decentralised energy trading; 4) green certificates and carbon trading; 5) grid management; 6) IoT, smart devices, automation and asset management; 7) electric e-mobility; 8) and general purpose initiatives and consortia. We have found that approximately one in three use cases is about decentralised energy trading, which includes wholesale, retail and P2P energy trading initiatives. The second most popular category is cryptocurrencies, tokens and investment accounting for one in five use cases. This is followed by IoT, smart devices, automation and asset management, and metering, billing and security, accounting for 11% and 9% of total use cases, respectively. Other projects make up 6–7% of the total (see Fig. 7). We also classify blockchain activities according to the platform and consensus algorithms used, wherever information has been made publicly available (see Figs. 8 and 9 respectively). 60% are as a starting point developing solutions based on Ethereum, while 55% have used PoW algorithms. However, it needs to be noted that Ethereum plans to switch to PoS and other consensus mechanisms such as DPoS and PBFT [120] in 2018. In addition, the majority of developers are oriented towards private permissioned platforms, which are most appealing for enterprises [21]. Energy Web (also an Ethereum-based blockchain specially designed for the energy sector) is being

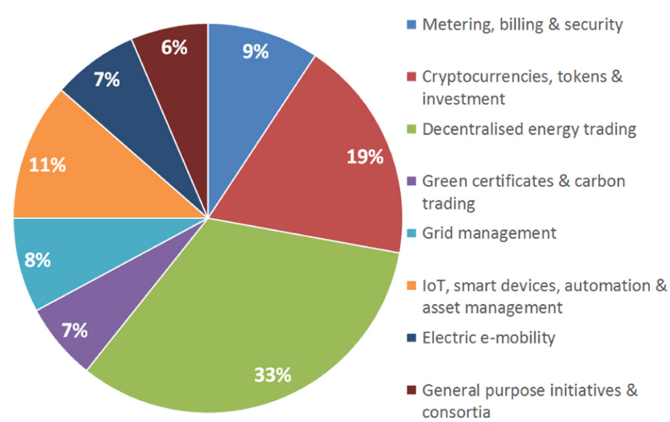

Fig. 7. Blockchain use case classification according to their activity field: results derived from a study on 140 blockchain initiatives in the energy sector being pursued by a large number of companies, startups and research institutions.

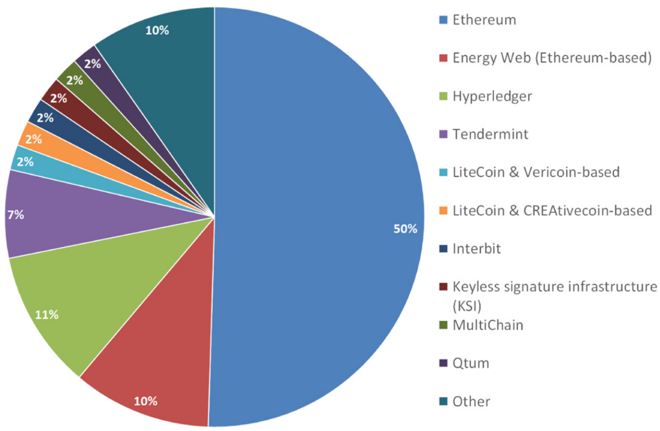

Fig. 8. Blockchain use cases in the energy sector according to blockchain platform used: results derived from a study on 140 blockchain initiatives in the energy sector being pursued by a large number of companies, startups and research institutions.

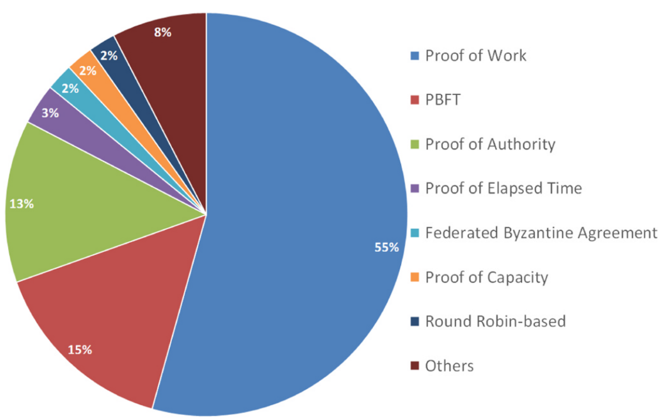

Fig. 9. Blockchain use cases in the energy sector according to consensus algorithm used: results derived from a study on 140 blockchain initiatives in the energy sector being pursued by a large number of companies, startups and research institutions.

explored by 10% of the projects, which have publicly revealed information on the platform of their preference. Energy Web is using PoAu consensus, a preferred solution for energy utility companies [43]. Other popular platforms include Hyperledger and Tendermint. Future development projects might see a switch towards more scalable, faster and more energy-efficient blockchains that will be exploring PoS or BFT-type of solutions.

4.1. Metering, billing and security

Several research initiatives are exploring blockchain technology use in metering and billing processes. When integrated with metering infrastructure, blockchains provide the opportunity for automated billing in energy services for consumers and distributed generators, which comes with the potential of administrative cost reduction. Blockchains offer traceability of energy produced and consumed at each end point informing consumers about the origins and cost of their energy supply, making energy charges more transparent. This opens up the opportunity for incentivising behavioural change and demand response. In addition, enhanced secure features of blockchains, could potentially be used to safeguard data privacy, identity management and resilience towards cyber-threats.

One of the first blockchain applications in the energy sector was the acceptance of cryptocurrencies for energy and electricity payments. In fact, an increasing number of companies accept payments with cryptocurrencies, amongst them several in the power and energy industry. BAS Nederland became the first energy company to accept Bitcoin as a new form of payment for energy bills [121]. This was quickly followed by other utility companies such as Enercity (electricity payments) [122] and Elegant [123]. With Enercity, residential customers can execute payments via the Internet and use automatically exchange Bitcoins to Euros. Elegant introduced cryptocurrency payments for energy services provision, including gas and electricity payments. More than 1 million Marubeni customers can benefit from 4% to 6% bill reduction, if they opt to pay their electricity bills with Bitcoin instead of fiat currencies [124]. Marubeni is also planning to expand cryptocurrency payments for various services and commodities, such as gas, water, mobile data and rent. Moreover, savings can be collected in cryptocurrencies as per customer choice. If so, savings are stored in digital wallets.

A South-African startup company, Bankymoon [125], is developing technological solutions that integrate Bitcoin payments into smart meters. Bankymoon is a blockchain services provider currently collaborating with Sarb, the South African Reserve Bank, to experiment with different regulatory policies on cryptocurrencies and their applications [126]. Smart contracts and automated transaction execution allows for real time settlement of payments for water, gas and electricity. The solution aims to overcome issues experienced in developing countries with delayed payments, debt and large numbers of unbanked population. In this vein, SunChain, a TECSOL startup that collaborates with Enedis, uses blockchain technology to certify, validate and automatically execute transactions between consumers and energy producers. Smart meter data are recorded in distributed ledgers, which can be shared with distribution network operators and energy suppliers and can result in traceable green energy generation and accurate billing [127]. PROSUME is developing a multi-solution decentralised blockchain solution platform that brings together power producers, consumers and utilities and a variety of applications [128]. PROSUME has developed a flexible platform that can be adapted to different operator needs, local infrastructures and regulatory frameworks. One application is the use of blockchains and data science for smart metering infrastructure and energy billing [128]. Pylon Network has developed a series of smart metering solutions powered by blockchain technologies. They have developed a smart meter, called Klenergy Metron, meters integrated with blockchain technologies that can trace and automatically record energy produced and consumed [129]. M-PAYG [130] is exploring blockchain technologies to provide pay-as-you-go solar services in developing countries. M-PAYG is installing rooftop PV systems in rural households, which are paid off in mobile payment increments, until full ownership transfer is achieved. PV panels are then connected to a control device that switches them on when payment agreements are honoured, and the procedure is repeated until ownership is fully transferred to beneficiaries. Services have been offered by use of mobile wallets, however M-PAYG is moving towards blockchain-based solution implementation that offers transparency, real-time monitoring and control of solar assets.

Apart from electricity, several companies are exploring blockchains for other metering systems, such as water and heat. Engie has set up blockchain infrastructure on a network of connected water meters that can trace water flows. They aim to develop a system that automatically decides on repair actions in the event of contingencies. Also, Engie has plans for similar applications for gas and electricity [131]. In addition, Engie recently announced a new collaboration with Air Products that will use blockchain technology to trace, verify and certify the green energy used in their manufacturing processes [132]. CGI and Eneco are exploring blockchains for heat meter data collection and billing. A pilot project was developed in Rotterdam, one of the largest heat networks in the Netherlands. The project was supported by the BlockLab initiative. Data collected by heat meters are stored in a shared ledger in the cloud. Data stored in blockchains can be accessible to different parties (four heat suppliers involved in the first stage of the pilot project) and therefore eliminate the need for cross-validation. According to CGI, this could achieve up to 50% savings in administrative management and form the core technology for reliable heat trading. In the future, project partners plan to apply this to a larger network that supplies with heat up to half a million homes in the Netherlands [133].

In the field of cybersecurity, Electron, a British startup, is developing a smart meter registration platform for gas and electricity and is researching advanced encryption techniques for smart meters [85]. One of the aims of the platform under development is to deliver consumer value by improving competition in energy supply services, facilitating consumer switching and mitigating fuel poverty. Electron is an ecosystem affiliate of the Energy Web Foundation, a research initiative supported by over 33 companies. Security from cyber-attacks in complex data exchanges in distributed generation applications is also the main focus of Guardtime, a research project funded by the Department of Energy, US [79]. Guardtime has developed a permissioned blockchain solution called Keyless Signature Infrastructure (KSI). Instead of using asymmetric cryptography, KSI uses hash-function cryptography and digital signature-based authentication, a solution that improves scalability issues such as the ones experienced in public ledger applications. KSI can offer veracity and version control of electronic data, systems or processes [134]. Moreover, Guardtime aims to combine blockchains, distributed infrastructure and cloud solutions that could lead to real-time energy exchange in microgrids [79].

In terms of challenges faced, a key prerequisite for applying blockchain techniques for smart meters is the availability of a working smart meter infrastructure. For example, in the UK, concerns in setting up a national Data Communication Company (DCC) that would provide a single point for collecting and distributing smart meter data to authorised users [135] has delayed considerably the rollout of the latest SMETS2 smart metering standard [136]. At least in theory, blockchain technology holds the promise of a more decentralised way to manage smart meter data, one that avoids the need for a single data authority such as the DCC, and hence avoids a single point of failure (Note that here by failure we mean either technical failure, or single point of attack by malicious hackers). In addition, integrating smart meters and distributed ledgers would come with a significant development cost, especially as smart metering infrastructure is already being rolled out in several countries without blockchain features. In addition this would require the development of new standards that would ensure interoperability.

Using blockchains to manage smart meter data also raises a host of security and privacy concerns. If blockchains or distributed ledgers are public, then all parties can be granted access to read the ledger of past transactions. Hence, to preserve privacy, this may require novel ways to anonymise information which would make energy consumption information not traceable to individual users. Assuring that a blockchain solution complies with legal privacy requirements, such as the EU's EU General Data Protection Regulation (GDPR) [137] could be even more challenging in a completely decentralised solution such as a blockchain, than for a conventional data service. Potential solutions could be using pseudonymity or permissioned ledgers where access to data will be restricted to authorised parties. Another important issue would be that of storage and data management of large, distributed ledgers.

4.2. Cryptocurrencies, tokens and investment

Cryptocurrencies are clearly one of the most popular and well understood application for blockchains, and new cryptocurrencies and energy tokens are increasingly emerging in the marketplace. Issuing a cryptocurrency specifically for an energy application can have some advantages, because the allocation and use of this cryptocurrency can be assigned to those with the highest stake in the system or providing the most socially useful service (for example, in a renewable energy application, generators can be rewarded with more cryptocurrency units if they generated the least carbon-intensive energy). Cryptocurrencies are used as a method to 'tokenise' assets that aim to create new markets or novel business models based on co-ownership and sharing of assets. An increasing number of enterprises are using cryptocurrencies as an instrument to attract investment and raise funding (also known as Initial Coin Offering or ICO). New cryptocurrencies can also be used to reward desired behaviours and facilitate green energy investments.

Specific examples include 4NEW, a UK startup offering a new energy token called KWATT [138], through an ICO process. 1 KWATT coin represents 1 kW of electricity per year of a waste to power energy plant co-located with a cryptocurrency mining farm. Coin owners can either decide to sell the energy to the UK national grid or use it to mine other cryptocurrencies, such as Bitcoin and Ethereum. Essentially, KWATT coin owners can avoid paying for the cost of electricity required to mine cryptocurrencies, which depends on the ever increasing energy consumption and increasing difficulty of the hashing algorithms [139]. Similarly to 4New, a US-based startup PRTI intends to build a waste-to-energy plant that will mine cryptocurrencies [30]. Envion, a German startup uses solar energy that would have been curtailed due to oversupply, to mine cryptocurrencies, while HydroMiner uses low-cost or stranded hydro generators in the Austrian Alps [30].

Several companies are using DLT and cryptocurrencies to facilitate green energy investments and asset co-ownership. Sun Exchange has developed a sharing economy blockchain platform aiming to crowdsale PV projects to potential investors [140]. DLTs keep track of ownership and revenues in immutable records and provide transparency required for regulatory compliance. Prospective investors can buy solar assets, which are subsequently leased to consumers in the developing world, typically local schools and small-sized enterprises. Smart contracts are used to automatically execute payments from solar producers to investors, as energy is being produced in near real-time. Blockchain-enabled solutions can reduce money transfer costs and increase security in cases of identity theft. Payments can be collected in cryptocurrencies or fiat currencies. Sun Exchange has successfully funded 5 solar projects with a capacity of 155 kWp so far, with one additional projects of 473 kWp in the pipeline near Cape Town, in South Africa. On top of regular payments from supported projects, investors can also collect 1 SolarCoin for every 1 MWh of energy produced. WePower, a Gibraltar-based startup, is developing a platform that brings together RES generators and investors interested in supporting global green energy projects. Renewable energy produced is tokenised and subsequently traded through the platform either to purchase electricity or exchanged for fiat currencies or cryptocurrencies. The platform uses blockchains and smart contracts [141]. Following a similar concept, ImpactPPA [142] aims to develop a decentralised platform for RES projects funding, based on Ethereum and smart contracts. The company has launched two energy tokens, one (MPAQ) sold to prospective investors to raise capital for communities that lack access to electricity, and the other (NRG) used by consumers for purchasing electricity to satisfy their energy demand and track green energy production data and transactions [142]. EverGreenCoin is a cryptocurrency designed for facilitating sustainable and renewable investments [30]. Another Ethereum-based platform is being developed by Solar DAO [143]. The distributed platform brings together stakeholders interested in the construction of solar plants. DAO tokens can be purchased and traded via the platform. System transactions are stored in a shared ledger and can be fully traceable and transparent. PROSUME has also introduced cryptocurrencies for green energy asset sharing, such as renewable and storage assets in community projects [128]. Green Energy Wallet, a German-based startup, uses blockchains to facilitate leasing of residential storage devices, such as home battery systems or EV batteries, to store oversupply from renewable sources. A novel approach is followed by Farad. The UAE-based company has issued a cryptocurrency that is based on the economic activity of manufacturing energy storage ultracapacitors. The cryptocurrency is based on Ethereum and smart contracts, and aims to commercialise intellectual property rights and encourage the development of energy storage solutions [144]. MyBit, a Swiss company, aims to incentivise investment in IoT services. They have developed a blockchain solution for investing and managing revenue generated by automation and smart machines. A decentralised investing platform relies on smart contracts and allows for crowdfunding of assets and distribution of revenue. In addition, MyBit has also developed MYDAX, a decentralised exchange for IoT assets [145]. A US-based startup, Local-e has launched a new cryptocurrency Sun-e that aims to financially support local and renewable energy investments. Sun-es coins are granted to solar producers for 100 kWh of verified energy produced [146]. A Brazilian startup, Dooak, has developed a marketplace that brings together sustainable energy projects and prospective investors. Business procedures are managed through smart contracts [30]. Other notable initiatives in the field of RES investment, include Assetron Energy in Australia and XinFin in Singapore [30].

Other companies, like SolarCoin, use cryptocurrencies to reward low-carbon and green energy production. SolarCoin is a cryptocurrency launched by SolarChange [147] in 2014. One SolarCoin is granted for every MWh of solar energy generated. The cryptocurrency is officially recognised by the International Renewable Energy Agency (IRENA) and can be exchanged for other cryptocurrencies or fiat currencies. According to CoinMarketCap, SolarCoin currently trades for$0.267473 (02/06/2018). SolarChange aims to incentivise and reward 97,500 TWh of global solar energy production within the next 40 years. 99.4% of the total number of SolarCoins have been premined (i.e. issued in the genesis block) to be granted to certified solar producers, while the rest will be generated using Proof of Stake for system developers. SolarCoin affiliates include ElectriCChain, a non-profit organisation that aims to achieve IoT solutions for solar projects worldwide. Energi Mine [148] uses Ethereum-based tokens (EnergiTokens or EKTs) to incentivise energy savings at a consumer level. Tokens are granted to anyone that can certify energy saving actions, such as buying an EV or reducing your energy consumption. A beta version of the rewards platform is currently available [149].

The Blockchain Development Company is planning to launch a new coin, RecycleToCoin, which will be available to end-users via a mobile app. The coin aims to reward individuals for recycling of plastic, steel and aluminum cans. Other recycling products will be added in the future. RecycleToCoin will be first launched in Autumn 2018 in Ayrshire (Scotland) and afterwards gradually will be rolled-out in more locations. Recycled items will be delivered to local collection points where customers will be provided with a unique QR (Quick Response) code that can be used to claim the reward. The blockchain solution is based on Ethereum [150]. Similarly, EcoCoin is a new cryptocurrency that aims to reward users for sustainable behaviour. Users are granted EcoCoins via a mobile app as a reward for sustainable actions, such as buying a vegetarian lunch or cycling to work. Actions can be verified by smart sensors, inspectors or certified vendors. The platform plans to go commercial by the end of 2019 and plans to use Proof of Stake algorithms [151]. EnLedger has developed EnergyChain, a blockchain platform for decentralised energy services. EnLedger supports registration of ownership of energy systems (generators, DERs, EVs, smart appliances) and distributed resources, renewable credits and certificates, energy metering data validation, automated tracking of availability, and automated payments for services provided in RES co-ownership models. Energy Efficiency Coin (EECoin) is the cryptocurrency used to facilitate the operation of the EnergyChain platform, which uses a proof of stake mechanism [152]. Enervalis and Grünstromjeton use cryptocurrencies to incentivise renewable energy generated and consumed locally. Enervalis combines energy monitoring with AI technologies and predicitive analytics to offer forecasting of supply and demand, and control of distributed resources in the energy system. They focus on microgrids, buildings and smart EV charging. In addition, Enervalis has issued NRGcoin, a cryptocurrency that enables energy system members, including household consumers, DSOs and energy supplier companies, to make energy transactions via smart contracts. Essentially, NRGcoin is an incentive and reward mechanism for more efficient use of renewable energy at a local level [153]. Similarly, customers in the Kamen region in Germany can accurately monitor in real-time the percentage of renewable energy provided to their households. As a reward they obtain Grünstromjeton tokens that can be exchanged for goods, fiat currencies or other cryptocurrencies. Transactions are processed by smart contracts in distributed ledgers [154].

Other notable initiatives include Greeneum and Inuk. Greeneum has launched a new token GREEN, used as an instrument for granting carbon credits and green certificates [155]. Inuk is an app that computes the real-time carbon footprint of everyday activities and links that to carbon credits. Their app proposes carbon offsetting activities such as investing in solar energy projects (or purchasing solar energy) to counteract the production of carbon. Blockchain technology is used to validate the real production of solar energy from blockchain-connected solar farms and to store transactions in a shared public ledger. Inuk beta version is planned for release in 2018 [156].

Overall, there are a number of key problems to be addressed when starting a new cryptocurrency. One core challenge is the overhead of implementing a cryptocurrency system, as well as issue of user trust in the long-term value of the new currency. For example, renewable generators may prefer fiat currency, if they believe the value of the cryptocurrency will not be sufficient to recoup their investments in practice.

4.3. Decentralised energy trading

Up to date decentralised energy trading has attracted the largest number of blockchain activities. Several applications are being developed such as wholesale energy trading, platforms that provide end-consumers with access to wholesale energy markets, and P2P energy trading platforms between prosumers/consumers.

In wholesale energy trading, blockchains can reduce transaction costs, while providing transparent data for access from several parties, including bodies that can certify regulatory compliance. Blockchains could eliminate the middle-man, reduce transaction costs and possibly trading volumes, and enable in this way small-scale consumers, to participate in energy markets [43]. Limitations in this space are related to the scalability and speed of transactions a blockchain system can support. In addition, a critical issue is that of commercial sensitive data being open-access to all counterparts. Platforms providing end-consumers with access to energy markets can unlock new flexibility services for the grid. In addition, such initiatives can increase consumer awareness and choice over their energy supply and could lead to faster switching and enhanced competition. Apart from limitations of scalability and speed, barriers in this space can be of legal and regulatory compliance. P2P local energy marketplaces can provide a solution for local optimisation of energy systems that can reduce strain on power networks or defer expensive reinforcements. In addition, local marketplaces may provide RES producers with additional revenue streams and can potentially decrease energy costs for end-consumers. Adding to the risks and limitations stated above, local marketplaces may seriously disrupt the structure of energy markets and might even increase grid defection. Balancing demand to supply is a critical issue that blockchain systems cannot solve alone. A combination of artificial intelligence (AI), machine learning and predictive analysis would be required to resolve such issues.

4.3.1. Wholesale energy trading

In the wholesale energy market space, PONTON aims to develop smart energy product trading solutions for regional markets using blockchain technologies [157]. The blockchain platform developed was successfully used to trade energy between Yuso and Priogen in 2016. Following the trial, PONTON partnered with more than 40 European energy trading firms and utility companies to develop a P2P wholesale energy trading platform that will support a broad range of traded products with physical delivery and will also focus on regional markets and different time frames like day-ahead, monthly, quarterly and yearly baseload for power and gas. In addition, PONTON is a key partner of the German Norddeutsche Energiewende 4.0 (NEW) project aiming to achieve smart trading of flexibility, balancing and local energy through their platform EnerChain [157]. Wien Energie, Austria's largest utility company, has launched a trial on blockchains for gas trading with the support of BTL, a blockchain startup. BTL announced the successful completion of a 12-week European energy trading blockchain pilot [158]. The trial showed there can be significant gains in costs and efficiency by the automation of trade processes such as confirmations, actualisations, invoice generation, settlement, audit, reporting and regulatory compliance. In addition, trading companies can benefit from reducing risks and cyber-attacks. The company uses Interbit, a combination of public Ethereum and privately developed software, which improves scalability and can support thousands transactions per second [159]. BTL has also announced the second stage of project called OneOffice for gas trading that aims to deliver cost savings across the trade life cycle [160]. The consensus algorithm used resembles that of Tendermint and PBFT and will be fully developed in the forthcoming future [161]. Energy giants BP, Shell and Statoil and other partners have started a collaboration with VAKT blockchain startup to develop a digital platform for energy commodities trading. Currently, trading involves paper contracts and backend processes that are prone to errors or fraudulent behaviours. A blockchain-based digital platform could reduce operating costs while enhancing security and transparency of trading records and digital documents. VAKT aims to develop a real-time DLT solution for physical energy transactions from entry to final settlement and payment [162]. The platform is expected to be operational by the end of 2018. In Singapore, the Platinum Energy Recovery Corporation is also developing platform for energy commodities trading, while PetroBloq in Canada, is developing an Ethereum-based platform for the oil and gas industry [30].

4.3.2. Energy trading support for small generators and end-consumers

Other blockchain projects focus on providing direct access of small and medium-scale consumers to central energy markets. In this area, Grid+ aims to develop a blockchain platform that will give direct access of consumers to wholesale electricity markets. Grid+ acts like an energy retail supplier that can provide consumers with savings in energy bills with the help of the Grid+Agent, an agent that makes automated smart decisions on energy trading on behalf of consumers [163]. Drift is an energy supply company that aims to provide customers with cheaper electricity prices and more transparent energy bills. Drift is currently active in New York but plans to expand in over 16 states. Currently it supports two tariff plans Go Green and Save Money offering 10–20% energy bills reduction [164]. Drift uses a combination of smart algorithms, based on AI and machine learning, high-frequency trading, and blockchains [30] with application in retail electricity markets. Consumers can purchase electricity in a P2P marketplace from local renewable or conventional sources. P2P transactions are recorded and processed by blockchains. Energy bills are issued every 7 days and include detailed information on energy fees and power mix used. Consumers can also track transactions via a web dashboard [165]. Similarly to Drift, Restart Energy, a Romanian energy supplier company, has developed a blockchain platform that enables bilateral transactions between consumers and renewable energy producers, that could achieve up to 30% reduction in energy costs [30]. SunContract has launched a decentralised platform for energy trading between generating units and consumers [166] in Slovenia. Consumers can choose their energy supplier and can achieve savings up to 40%.

In the Netherlands, Alliander deployed blockchain connected smart meters which were used for real-time settlement and trading between residents, and residents and the wholesale market [83]. The Alva project took place in the Dutch island of Texel, where an active network management system is put in place. Smart meters were linked to Ethereum blockchain via Raspberry Pi 3. Metering data were used to enable smart contracts and transactions between residents that are recorded in a public ledger. System operation is monitored by visualisation tools and end-user mobile apps [167]. The Alva pilot project revealed speed, performance and scalability issues of the tested technology. At the same time, the potential of blockchain technologies was also revealed. Energy21 and Stedin have a blockchain solution that enables local energy markets to transact with each other and with wholesale energy markets. This forms a layered energy system that links local energy markets and microgrids to wider national markets taking a system and market-based approach rather than depending on P2P energy transactions. According to Energy21 and Stedin, this approach could lead to more efficient operation of the energy system by taking into account network constraints and incentivising energy balancing and flexibility services [168]. The solution used is a consortium blockchain system developed by Quantoz [169]. Stedin is a partner of the Energy Web Foundation.

In Singapore, Solar Bankers has developed a P2P energy trading platform that connects small solar generators to energy markets. They have created their own consensus algorithm called Obelisk, which is reportedly more scalable and energy-efficient than traditional proof of work algorithms [170]. Obelisk runs on a Skycoin blockchain and does not require hardware mining but manages validators according to a web of trust, where each node subscribes to other trusted nodes. Blocks are then signed by the most trusted consortium, and each node's actions are recorded and audited to prevent any malicious behaviour [171]. Skycoin claims to achieve transaction times of up to 2 s. Solar Bankers have plans for testing their technology in pilot projects in Turkey and Dubai [170].

Another blockchain startup, Volts Markets, aims to remove the intermediaries in the energy market by developing a P2P decentralised energy trading platform. The platform is based on Ethereum and it is able to originate, track, manage and trade energy [172]. In Brazil, CoSol enables P2P energy trading between consumers and small-scale energy producers. Energy traded is recorded by power meters that are linked to an Ethereum blockchain [30]. Similarly, Pylon Network is developing a decentralised platform for energy trading between RES generators and consumers without intermediaries. They plan to reward green energy generation with a token called Pylon-coin, which can be traded through the platform [173]. Pylon Network has developed its own open-source blockchain solution to address energy industry needs. Their solution is based on a LiteCoin and CREAtivecoin fork that offers lower energy cost per transaction and can provide larger throughput of up to 7000 transactions per second. The consensus algorithm used is Proof of Capacity [76]. Pylon Network are currently trialling their technology solution in a pilot project in Spain [129]. Tal.Markt is a digital platform developed to facilitate direct renewable energy supply from local and regional producers to consumers. Tal.Markt aims to provide additional revenue streams to renewable producers in Germany, as other financial incentives are gradually being removed [174]. elblox is the blockchain platform used to guarantee the origins of green energy at 15 min time intervals [175]. PROSUME has developed a decentralised energy exchange platform for P2P transactions including services for local aggregators. They also aim to use their platform for gas and oil trading [128]. Finally, a notable initiative is undertaken by Electrify.Asia. They have developed a decentralised platform where consumers can directly purchase energy services from generators or energy suppliers [30].

4.3.3. Blockchain trading for utilities and energy system stakeholders

Several projects aim to provide platforms open to all energy system stakeholders. Bittwatt aims to develop a digital platform based on Ethereum, open to distribution and transmission system operators, regulators, energy suppliers, producers and consumers. Blockchain protocols will be used to share and synchronise near real-time operational information between stakeholders enabling a decentralised service for energy delivery, balancing, metering and billing. The platform uses AI techniques to achieve demand response services and market forecasts. Bittwatt matches and settles market offers of supply and demand in one hour settlements. In the case of P2P settlements Bittwatt proposes the use of a new cryptocurrency BWT [176]. Clearwatts is developing a distributed platform where different stakeholders (renewable generators, utilities, grid operators, regulators) can share reliable information on a real-time basis for energy trading and settlement of power purchase agreements, such as price information [177]. They are collaborating with blockchain developers BigchainDB and Spherity [30]. According to BigChainDB, they have developed a blockchain database solution that achieves simultaneously desired blockchain properties (decentralisation, immutability etc.) with low latency and high transaction rates [178].

Having started with provision of smart IoT solutions to manage household energy usage, Green Running is proceeding with the development of a decentralised platform that will enable P2P energy trading. The proposed market model and ecosystem includes transactions between energy suppliers and local aggregators, who serve as a broker function at local energy system communities comprising several hundreds homes. Local aggregators can be utility companies, commercial aggregators or community groups and will enable prosumers and consumers to transact on the blockchain-based platform. VLUX energy token plays an important role to support transacting between different players within the ecosystem. VLUX however will not be used for direct trading between household consumers, but fiat currencies, to avoid consumer confusion. Energy trading at this level will be achieved by automation, however consumers will be able to specify individual preferences. Prices in the resulting P2P marketplace will account for network usage and grid operation fees. The decentralised platform will be based on Ethereum and smart contracts and will use proof of authority. Each local network will have a local ledger. Local aggregators are planned to play the role of validators. Transaction digests from all local networks will be stored in the public Ethereum blockchain [179]. OMEGAGrid has developed a P2P energy platform with special focus on utilities and grid balancing. They are involved in several pilot projects, such as the Stone Edge Farm Microgrid and Accel-VT at Burlington, Vermont, and are supported by several utilities in the US. OMEGAGrid matches consumers to local energy projects. Utility companies can reduce costs or defer network reinforcements by improving grid balancing and settlement. Private blockchain ledgers can record communication, confirmation of power delivery, dynamic network management, and automated settlement of transactions [180].

4.3.4. P2P trading in community projects and microgrids

Several projects focus on local marketplaces and P2P trading in community projects or microgrids. LO3 Energy partnered with Transactive Grid to develop a community microgrid in New York [181] (presented in more detail in Section 3.5.2). The company achieved the first P2P blockchain transaction between a residential PV producer and his neighbour. Since then the company has announced more pilot projects. In partnership with energy provider EnergieSudwest and Karlsruhe Institute of Technology (KIT) they are developing a local energy market in the Lazarettgarten microgrid in Landau, Germany. Solar panels and energy storage devices are part of the microgrid. The project focuses on market mechanism design and regulatory changes required for further roll-out of similar local marketplaces [182]. With Allgauer Uberlandwerk they will test blockchain technologies in the Allgau microgrid. They aim to investigate the interest of consumers in such markets and how local microgrids and marketplaces can be integrated into existing energy systems [183]. In Australia, in partnership with Yates Energy Service, they aim to investigate transactive energy market models that promote generation from renewable sources and energy conservation [183]. In addition, LO3 Energy is planning to start a project in Texas with Direct Energy focusing on commercial and industrial consumers of energy [183]. In the UK, LO3 Energy and Centrica are planning to develop a local energy market in the network constrained area of Cornwall, that aims to reduce high renewable curtailment [184].

Power Ledger is an Australian startup involved in a variety of blockchain applications for energy systems. The most mature application is the development of a residential P2P electricity trading marketplace between prosumers and local consumers, the first of its kind in Australia. The startup ran a trial and demonstrated significant potential for energy bills savings and additional revenues for PV producers. For example, PV prosumers are typically payed 7c/kWh when exporting excess power back to the main grid, while consumers are charged 25c/kWh. Power Ledger's P2P pilot project agreed a pricing scheme of 20c/kWh of energy purchased through the platform. 75% of electricity charges went to prosumers and 25% to the utility company. In future deployments, a small cut will be taken by the blockchain platform developers [185]. In addition, Power Ledger partnered with Vector Energy, New Zealand's largest energy distribution company, and implemented the first P2P blockchain-enabled energy trading platform across a regulated distribution network in Auckland. The company recently raised $34 million AUS dollars through sales of their POWR cryptocurrency, which is tradable on the public Ethereum blockchain. POWR can be converted to SPARKZ, the marketplace's native currency, which can be traded for electricity on the company's private blockchain. Power Ledger is also active in the fields of wholesale electricity trading, electric e-mobility, IoT/smart devices and automation, grid management and green certificates/carbon trading, however most activities in this space are still in the early development phase with beta releases planned in the end of 2018 [185]. Power Ledger is involved in more pilot projects in several countries including Tasmania, India, Thailand and Lichtenstein. Power Ledger has also partnered with Kepco, the Kansai Electric Power Corporation. They plan to examine blockchain feasibility for trading excess energy of prosumers, who may own generating or storage device assets. The initial trial will take place in Osaka, Japan and will involve trading between 10 households [186]. Vector, the largest electricity and gas distributor in New Zealand, are testing a P2P local energy marketplace in New Zealand, developed by Power Ledger. Participants in this ongoing project include 500 residential PV prosumers, schools and community groups [83]. Vattenfall also run a blockchain trial of Powerpeers [187], a platform that enables energy trading through a P2P network, where individuals determine from whom to buy or sell self-generated electricity, but they opted out for a conventional platform solution. In Japan, the Eneres project involves more than 1000 households, energy prosumers that own PV, small wind generation or CHP that can trade their energy surplus with other households through blockchains [188].

In Amsterdam, The Netherlands, Alliander is collaborating with Spectral Energy to develop a P2P energy sharing platform, called Jouliette at De Ceuvel in Amsterdam [189] on the basis of a private and permissioned blockchain solution that can achieve faster transactions and improve performance. Spectral Energy has launched an energy token called 'Jouliette' that can be used to facilitate P2P energy transactions. De Ceuvel is a private behind-the-meter smart grid which consists of 16 office buildings, a greenhouse, a restaurant, a small hotel and several photovoltaic (PV) panels. Energy is exchanged within the smart grid on a P2P fashion. The Jouliette platform can display real-time power flows of the community and uses AI algorithms to predict energy production and consumption [189]. MultiChain, the blockchain platform used, allows public/permissionless and private/permissioned blockchains. In the latter case, the consensus mechanism deployed uses a round-robin mechanism to allocate block generation amongst a set of known validators [190].

In France, Bouygues Immobilier is collaborating with the city of Lyon to develop a blockchain demonstrator project for direct energy exchanges between solar producers and energy consumers. Blockchain technology is used to authenticate and verify the energy produced and consumed at different locations in the system, as energy is exchanged between different flats in a building. Smart contracts are used to derive geolocation of nodes in the system that enable accurate calculations of power losses as energy is being transmitted [191]. Blockchain infrastructure is developed by Stratumn. The consensus algorithm is called Proof of Process. Verification of data is decoupled from the source of data creating a zero-knowledge proof e.g. system members can verify that a contract has been honoured without knowing the exact terms of the contracts itself. Proof of Process uses typical KYC techniques thus represents a more centralised blockchain approach where network members follow a hierarchical order of trust [192]. Conjoule focuses on P2P energy trading in local communities, where prosumers can sell their energy surplus to local households or organisations. They are involved in two pilot projects in Kettwig and Mulheim, in Germany [193]. The German startup, supported by Innogy and TEPCO, is also developing a distributed platform where energy producers, consumers, energy storage and flexibility providers can transact without central management [194].

Divvi is an Australian startup company that aims to develop a distributed marketplace for renewable energy with focus on community energy systems and new business models for renewable energy ownership. The distributed platform is based on Ethereum smart contracts [195]. In the same application area, Energo Labs is a Chinese startup company that utilises blockchain solutions for community energy projects comprising prosumers, consumers, energy storage and smart grid devices to enable P2P energy sharing. Energo Labs envisions achieving decentralised and autonomous energy systems, where members of communities or microgrids can exchange energy, information and payments in real-time. Energo Labs uses two tokens: the WATT token is equivalent to 1kWh of energy stored in the microgrid or storage asset, and TSL a cryptocurrency that enables access to the microgrid energy storage systems. TSL are premined and 80% are distributed to storage owners. Energy consumption at a local level is prioritised. Quantum blockchain moves away from PoW solutions and enables a decentralised app development platform, integrated with smart meters or EV charging stations. P2P energy trading pricing mechanism is similar to the operation of stock markets and order book tables. Automated trading is accomplished by use of intelligent agents and use of user mobile apps. Energo Labs has successfully demonstrated their solution can successfully collect data from production and consumption ends. In 2018, they plan to control energy use by AI and a smart home app. They have projects planned for Philippines, Australia and South East Asia in the scale of hundreds MWs [196].

Energy Bazaar focuses on local energy markets in emerging countries and particularly in India. They aim to facilitate energy exchanges for households, commercial consumers, microgrid operators, utilities and transmission operators. The company aims to develop a suite of technologies such as smart software agents, AI for enhanced forecasting of energy production and consumption, and game-theoretical market design that will provide incentives for flexibility services and matching of supply and demand. Blockchain will form the trust layer that enables transactions between different stakeholders [197].

In Denmark, BLOC or Blockchain Labs for Open Collaboration is a digital solutions company involved in two projects in Copenhagen and Samso. EnergyBlock is a community pilot project in Copenhagen that investigates local and community energy markets, and sensor retrofitting for use with blockchains [198]. They are also involved in a project in Samso, Community Power that aims to investigate how blockchain technologies can enable co-ownership of energy assets, retrofitting existing RES assets for connections into blockchain systems and data verification for participation in energy and carbon trading markets [199]. Greeneum is focusing in combining artificial intelligence and machine learning techniques with blockchains to develop a decentralised energy market that allows payment settlement and real-time energy transactions. Greeneum has been involved in pilot projects in Israel and Cyprus [200]. Oursolargrid focuses on community energy systems and P2P energy trading between prosumers and consumers at a local level, powered by Ethereum. They believe that consumers might be willing to pay a premium for locally produced renewable energy, which can prove to be an additional incentive for RES investment [201]. Power-ID is a P2P energy trading pilot project in Switzerland between 20 prosumers and consumers. The project will investigate the potential of DLT for fairer network costs and lower grid operation costs. According to a recently published report [31], project developers are still exploring both public and private blockchain solutions. StromDAO, a German startup, offers a platform where consumers can invest in community and renewable projects and reduce their energy bills. They aim to provide blockchain solutions for energy system stakeholders in compliance with conventional energy market structures [202]. StromDAO is based on the Fury Network blockchain [30] and uses Proof of Authority.

In the Netherlands, ToBlockChain has developed a P2P digital platform for energy exchange, called PowerToShare. Energy transactions are managed through a token mechanism [203]. PowerToShare is currently being tested at the Green Village project in Netherlands [204]. In Switzerland, Hive Power uses blockchain-enabled smart meters to verify quantities of energy produced. Enabled by an Ethereum solution and smart contracts, prosumers can engage in decentralised energy trading. In Thailand, BCPG has developed a blockchain-based application that eliminates all intermediaries (such as energy suppliers and utilities) and enables P2P energy trading between consumers [30].toomuch.energy is a blockchain startup that aims to create a P2P platform for consumers and energy prosumers [205]. OneUp are software developers specialising in data analytics and blockchain technologies, with expertise in the Ethereum platform [206]. OneUp was awarded for developing a decentralised energy trading platform at a startup competition in 2017 and has been supporting several companies interested in blockchain technologies, most notably PWC [30].

4.4. Green certificates and carbon trading

Several developers are working on the use of blockchain technologies for renewable or carbon certificates, their automatic issuance and trading. Current market structures for renewable certificates, carbon credits or general environmental attributes are fragmented and complex. Small energy producers are in practice excluded from claiming carbon credits due to high costs associated with the procedure. In addition, audit processes are often performed manually by a central authority, therefore are prone to errors and even fraud. Blockchain systems can automate green certificates issuance (including for low volumes of energy), reduce transaction costs, they could create a global market for such assets, increase transparency in the market and prevent double-spending. Limitations for a blockchain system in this space is the certification and verification of provided services. For example smart meters integrated with blockchain solutions could automatically certify one's energy production, however the potential of tampering with such systems is not yet explored.

Nasdaq, the first global stock exchange to explore distributed ledger technologies [207] ran a successful green certificates trading pilot in 2016. Solar producers were granted certificates with technology developed by Filament, which were next traded online via Nasdaq's Linq platform. Volts Markets use smart contracts to automatically issue and track renewable energy certificates via an energy assets exchange platform [172]. Veridium has launched an Ethereum-based platform for trading carbon credits and natural capital assets through their token TRG [83]. Poseidon is developing a platform that will use smart contracts to trade and track carbon credits based on Stellar (FBA or BFT based) blockchain [208].

Based in Russia, DAO IPCI is a Russian startup company that aims to provide integrated services for carbon and environmental assets based on blockchain and smart contracts. According to DAO IPCI, current carbon markets are fragmented across multiple registries, platforms and trading schemes. They aim to develop an open-source blockchain solution that will create an immutable, trusted and decentralised platform that will allow for more efficient coordination between stakeholders. Mitigation Token (MITO) is used as an exchange currency to execute smart contracts on environmental assets trading [209]. CarbonX aims to incentivise sustainable and eco-friendly consumer behaviour by use of blockchain technology. CarbonX is assessing a variety of products and services in terms of their carbon footprint to inform a rational energy behaviour. Consumers are further incentivised when purchasing carbon-neutral products with GOODcoins [210]. CarbonX aims to develop a solution for P2P carbon trading between consumers and has partnered with ConsenSys, an Ethereum-based blockchain provider [211].

Energy-Blockchain Lab, a Beijing-based collaborative initiative on energy and environment blockchain applications and a member of China Green Finance Committee, has partnered with IBM to create a carbon credit management platform that uses Hyperledger Fabric. The platform aims to reduce the costs of China's national carbon market by 30%. Energy Blockchain Labs provides blockchain financial services to businesses aiming to improve their energy saving and sustainability agenda. In partnership with IBM, they aim to create a decentralised platform for trading carbon credits and other environmental attributes. IBM and Energy Blockchain Labs aim to reduce the 10-month average carbon asset life cycle in China from 20% to 50%, which can lead to significant operational cost savings [212].

Based in Austria, Grid Singularity aims to provide several blockchain solutions for the energy sector, including trading of green certificates [213]. Grid Singularity is a founding member of the Energy Web Foundation [72]. Power Ledger is also developing a carbon trading use case for blockchains [185].

4.5. Grid management

Several blockchain developers are working to explore innovative solutions based on automation and decentralised grid management and control. Potential benefits in this field are the potential for improving balancing of supply to demand, better coordination between transmission and distribution system operation, automated verification of grid assets and improvement in visibility of distributed resources and assets [43]. Blockchains face several challenges in this space. Foremost, blockchain systems need to improve significantly in providing higher throughput and transaction speeds that would allow real-time verification. Metering, grid infrastructure, control and communication systems already being deployed in power networks would need to be connected to distributed ledgers. This would result in the generation of massive new datasets, which need to be carefully managed and safeguarded by potential cyber-attacks.

Significant initiatives in grid management are presented below. PONTON has developed Gridchain [214], an innovative pilot software based on blockchain technology that simulates future processes for real-time grid management. The tool aims to achieve greater coordination between TSOs, aggregators and DSOs and to provide solutions for grid congestion management. Moreover, Gridchain aims to contribute to the European standardisation of communication technologies for future smart grids [214]. Grid Singularity, a founding member of the Energy Web Foundation, is also working on providing smart grid management solutions [213].

In the Netherlands, TenneT was the first power grid operator to trial blockchain connected residential batteries that provide grid services [215]. German company Sonnen is using battery technologies to reduce the need for emergency measures and reserves and to provide additional flexibility at periods of grid constraint. The two companies successfully ran a trial in Germany that redispatches available assets to prevent network bottlenecks using a network of distributed storage to absorb oversupply from wind generators. The blockchain platform informs the network operator about the availability of flexibility measures and records their contribution in the blockchain. Future plans aim to further explore the blockchain potential with an open source solution provided by IBM [216]. TenneT is also planning jointly with Vandenbron to run a pilot project using vehicle-to-grid for balancing and ancillary services. A blockchain platform will enable EVs to participate by recording their availability and their response actions to signals from the system operator [215]. A blockchain platform developed by PROSUME aims to reduce network costs by improving load balancing with energy storage devices and transmission exchanges [128]. EvolvePower develops blockchain solutions for energy utility companies and grid operators, enabling them to get better visibility, access and control over data at the grid edge. This enables faster control over demand response services [217]. EvolvePower is an ecosystem affiliate of the Energy Web Foundation [72]. Filament aims to provide grid operators with IoT solutions for more efficient management of transmission and distribution networks [218]. Power Ledger has also been reported to developing solutions for microgrid operation [185]. In the UK, Electron has partnered with Slock.it to provide solutions for designing more efficient, resilient and flexible systems for the UK market. The British startup aims to develop a collaborative trading platform for all demand-side response assets and P2P trading in microgrids [219]. Electron has also built a demo platform representing the UK energy market based on Ethereum and showed that customers can switch energy suppliers up to 20 times faster, when blockchain technologies are deployed. OurPower is a not-for-profit energy supplier in the UK. The company received UK public funding to research the potential of DLT in local balancing of rural and decentralised energy networks with high RES penetration. The feasibility study project called Community Energy Dynamic Solution with Blockchain (CEDISON) will conclude in October 2018 [220], and will be followed by a larger trial, in case it is successful. More broadly, a consortia of UK distribution network operators are investigating the technical and commercial potential of blockchain technologies and smart contracts for distribution network operation and impact of disruptive technologies to the transition to system operation [221]. This project will conclude in 2020.

4.6. IoT, smart devices, automation and asset management

Blockchains could enable IoT platforms and asset management. Several research projects, startups and trials have already been deployed and are summarised below.

Filament provides blockchain IoT solutions such as smart metering, real-time monitoring, asset tracking and asset management. They have raised $6 million to develop technologies that allow electronic devices to be connected online in blockchain platforms. Filament enables smart devices to blockchain transactions that can integrated in different distributed ledger architectures by use their Blocklet solution [218].

In Germany, Slock.it aims to develop IoT applications and a platform for sharing economy, named the Universal Sharing Network [222]. They have partnered with Siemens, Innogy RWE and Samsung and are currently supporting various research projects that aim to accelerate the development of Ethereum and smart contracts technologies. Slock.it is also an ecosystem affiliate of the Energy Web Foundation and is currently working towards implementing solutions on the Energy Web blockchain and Proof of Authority [72]. Dajie offers a software solution that is installed in IoT devices or own integrated hardware and software IoT devices. Energy generated by prosumers creates coins that are stored in a digital wallet. One coin corresponds to every kWh generated. Coins can afterwards be used to claim carbon credits, pay for energy services or used to facilitate P2P energy trading in local communities and microgrids [223]. ElectriCChain is the blockchain solution that powers the SolarCoin digital asset. ElectriCChain is a non-profit organisation actively involved in 12 solar blockchain-related projects with several partners including Bitseed, Chain of Things, Ethereum, Grid Singularity, IOTA and SolarCoin blockchains [224]. ElectricChain aims to collect live solar data into a single blockchain from more than 7 million solar projects worldwide. The scientific database aspired will collect data from monitoring devices (solar inverters, data loggers, Raspberry Pis) and connect with the SolarCoin blockchain. In this way, solar producers will be rewarded for their generation with SolarCoins [225]. Power Ledger is working on autonomous smart asset management with blockchains [185].

Fortum, a Finnish energy company, offers a blockchain-based solution that enables consumers to control appliances over the Internet in connected homes, and therefore optimise their energy demand and reduce energy bills. The platform provides an integrated solution that takes into account weather forecasts, energy demand forecasts and real-time electricity prices [226]. AdptEVE is an energy application that aims to optimise energy management in solar buildings and homes with the help of data-driven techniques. According to the developers, AdptEVE can activate smart contracts for energy exchange and record transactions and revenue earned almost in real-time [227]. Green Running, a British startup is developing artificial intelligence solutions to predict individual dwellings energy demand, prosumers projected generation and forecast electricity market prices with the use of an AI-driven home energy assistant Verv. These parameters determine optimal scheduling and decision-making for a potential P2P market between homes with solar PV and battery assets enabled by blockchain technologies [228].

In Switzerland, Tavrida Electric, one of the world's largest electric equipment suppliers, has partnered with Qiwi, the Russian system operator, to use blockchains for energy transactions traceability. Transactions are recorded on the open ledger and can be visible to regulators and other energy companies [229]. Wanxiang, the largest Chinese multinational automotive components manufacturer based in Hangzhou, China, plans to invest $30 billion in the Hangzhou smart city project. Wanxiang has launched a new startup accelerator to fund blockchain initiatives that align with the project's objectives. The initiative has grown into a research institution named 'Chainbase Accelerator', which will initially support four startups. This includes Dorling Abby, which is looking to develop assets and smart devices management with blockchains and smart contracts [230].

Based in the US, Oli is focusing in optimisation of energy system components, such as single power plants, demand services, storage providers but also more complex energy systems comprising multiple components. The energy system consists of many 'energy cells' that need to work in collaboration to achieve desired operation. These 'energy cells' communicate with each other via blockchain technology. Essentially, Oli uses blockchains to enable virtual power plant operation that can also provide grid services. Oli has developed a software platform that outsources tasks such as data storage and optimisation to cloud services [231]. They are an ecosystem affiliate of the Energy Web Foundation [72]. Swytch has developed a decentralised platform that certifies and rewards sustainability efforts with a Swytch tokens. Tokens will be produced by smart meter data, IoT devices, EVs, storage systems and other smart devices that can be used to reduce CO2 emissions. Swytch tokens will be created in an energy-efficient permissioned blockchain environment that avoids proof of work mechanisms. Swytch is currently testing their key parts of their platform in collaboration with e2m, a large aggregator of renewable power in Europe [232]. Wirepas, the IoT provider, has been testing blockchain technologies in collaboration with the Energy Web Foundation. They aim to connect IoT devices to distributed ledgers, especially devices deployed on the consumer side or the grid edge [233].

Based in southern France, Daisee aims to deliver distributed and reliable data from energy and physical infrastructures that can be shared by all energy system stakeholders. Daisee has been involved in several field trials at rural locations like Prats-de-Mollo and urban locations like Villeurbanne. The focus of both projects is optimisation of energy self-sufficiency and consumption [234].

The US Department of Energy released in 2017 a call for blockchain-based pilot and demonstration projects for energy systems that rely on fossil fuels. The call aims for public, transparent and tamper-proof architectures that would bring about significant advances in both security and reliability. Industrial IoT applications that utilise embedded intelligence and real-time data from smart devices were strongly encouraged [235]. Intrinsic ID is able to authenticate and encrypt IoT components on a semiconductor level bringing about security and traceability in the hardware level. In partnership with Guardtime, they have applied their technology solution to electricity smart metering systems. The solution introduces trusted and reliable input data that correspond to real energy production and consumption, which are thereafter stored in distributed ledgers.

Blockchains need to overcome challenges related to their performance and scalability to prevail in IoT services and applications. In addition, monitoring and recording the energy use of each individual device could be construed as intrusive and raises privacy. Hence, new standards would need to be developed not only to achieve interoperability of smart devices and automation, but also to prevent hacking and protect the privacy of individual users.

4.7. Electric e-mobility

Blockchain technologies have also been explored by a large number of companies for their use in EV applications. Electric vehicles and e-mobility are a natural application for blockchains. The decentralised nature of transport, with many parties (vehicles, drivers, charging stations, passengers using on-demand mobility services such as Uber of Lyft) lends itself naturally to blockchain implementations. Advantages of decentralisation in this case include: elimination of the need of a centrally managed EV charging infrastructure, fault tolerance, as well as elimination of price-setting and collusion between charging stations or transport providers. However, also in this application, blockchains would have to overcome serious privacy and security concerns. Blockchain solutions aim to provide incentives for privately-developed EV charging infrastructure. With blockchain-enabled solution EV owners can gain greater transparency in energy charges and can potentially have greater choice in selecting their energy supply. Moreover, what blockchains offer as an advantage to other solutions, is a unique verification and communication platform that would work in different locations, including cross-border travelling. For the network operators, blockchain systems offer a market-based solution that could be used for optimised management and coordination of EV charging.

Share&Charge, a platform developed by Innogy Motionwerk and Slock.it, allows P2P transactions between EV drivers and private EV charging infrastructure owners. The EV charging stations network runs on public Ethereum and smart contracts. Users have an electronic wallet that gets access to real-time information on prices and transactions within the network. Any member of the network can monitor and track all transactions. The platform achieves automated billing and can incentivise building EV charging infrastructure, as privately owned charging stations can generate revenue streams by enabling other drivers to charge EVs at their points. Innogy has launched hundreds of EV charging stations across Germany since May 2017 [236]. Share&Charge has recently joined the Energy Web Foundation initiative and aims to develop EV charging solutions in the Energy Web blockchain. They have also partnered with Oxygen Initiative, a US-based company, to use their Share&Charge platform for real-time payment settlement in EV charging stations. Charging arrangements can be flat, time-based or kWh-based tariffs. Charging station owners can also specify special tariffs for family and friends. Oxygen Initiative is planning to expand the platform for settlement of tolls payments and car-sharing [237]. eMotorwerks [238], a California-based company, started a pilot project on EV charging in July 2017 that also uses Share&Charge. eMotorwerks offers JuiceBox a smart wifi-connected EV charger that can be controlled via a mobile app. Consumers can get greater control over charging patterns, cost and power generation mix used for charging.

In the Netherlands, Alliander is conducting trials on dynamic customer contracts for EV charging arrangements [83]. Customer commercial arrangements are achieved through smart contracts in the Ethereum platform. Their blockchain solution aims to allow EV owners to choose and automatically pay their desired energy supplier at every charging station while providing transparency on energy prices and contract terms [167]. Based in Germany, Car eWallet has developed a blockchain transaction platform that integrates several mobility services, such as car charging from different energy suppliers and charging stations, parking, car-sharing and car rental, with vehicles and infrastructure. Car eWallet removes the need for a central trusted authority by using a shared ledger developed in Hyperledger technology. Payments can be automatically or manually processed depending customer's choice [239]. PROSUME has developed a decentralised platform for EV management and data collection [128]. Energo Labs is involved in developing EV charging stations for coordination of EV charging and automated payments via digital wallets empowered by blockchain technologies.

Another example is Everty, an Australian startup company that has built a platform for EV charging that works for private, semi-public or public EV charging infrastructure. Drivers can charge their EVs at home, commercial or public charging stations while having full control of owned stations and charges [240]. Power Ledger is also working on e-mobility applications [185].

Opportunities for blockchain innovation in e-mobility applications are significant, however certain challenges need to be addressed. Blockchains are by their nature public ledgers, so information about the daily location and movement of EV users would need to be anonymised, to protect their privacy. Moreover, blockchains in e-mobility systems would have to be tamper-proof, to prevent malicious actors endangering the safety of EVs. Finally, given that EVs can interact with the power system and charge in a number of locations, the development of standards for interoperability is crucial to achieve the benefits blockchains can offer in this space.

4.8. General purpose initiatives developing underpinning technology

In addition to commercial activities focused on specific application domains, several organisations have established collaborative platforms that aim to explore blockchain potential in a variety of use cases. Among the most important is the initiative taken by Eurelectric, the European electricity industry association, who launched an expert platform that aims to investigate the potential of the blockchain technology across the electricity value chain including generation, trading, supply and networks [43]. Eurelectric's Blockchain platform comprises 24 energy companies active in the European Union and has recently published a report on blockchains in the energy industry [241].

The Energy Web Foundation (EWF), a global non-profit organisation focused on accelerating blockchain technology across the energy sector, was founded by Grid Singularity and the Rocky Mountain Institute, followed by more than twenty four companies and nine ecosystem affiliate companies. EWF has secured $2.5 million in funding to identify and assess the most promising use cases of blockchain technology in the energy sector and launch a new energy-focused blockchain platform (‘Energy Web Platform’), suitable for implementing these use cases at scale. EWF uses a consensus algorithm developed by Parity Technologies [242]. In April 2018, EWF launched the beta version of a public test network Tobalaba for the Energy Web blockchain, an open source platform specially designed for energy sector. The platform is based on Ethereum but aims to achieve better scalability and faster finality of transactions by use of a Proof of Authority algorithm, called Aura. With PoAu, blocks are generated by special nodes known as authority nodes in a round robin fashion where each validator is assigned a time slot per round to create or sign a new block. In Aura and Tobalaba, consensus on different chains that might come up in the case that nodes go offline is determined by chain scoring, meaning that eventually nodes switch to the chain with the largest height. Finality can be reached when the majority of validators (51%) signs the chain and then signs it again, meaning that transactions are final and cannot be discarded as a result of further reorganisation of multiple chains [243]. The platform also uses a governance structure giving special permissions in control layers that can suite well different actors in the energy system. Finally, Tobalaba offers a 3 s block time that can achieve higher throughput, and EWF plans to further improve the blockchain's scalability [72].

Hyperledger (Linux Foundation) is an open-source collaborative initiative aiming to provide innovative solutions for enterprises in the blockchain space [47]. IBM is a founding member of the initiative that researches different consensus algorithms for blockchains that can be fast, scalable and energy-efficient. Hyperledger has developed several blockchain platforms such as Hyperledger Fabric and Hyperledger Sawtooth and are developing several consensus solutions including PBFT and PoET.Other notable initiatives include the Blockchain Research Lab, which aims to explore the potential of blockchains for developing whole energy systems. Their vision involves combining smart meters, blockchain technology and real-time auctions to create an integrated energy market, which would reduce existing power system imbalance costs and improve overall system efficiency [244]. Blockchain Futures Lab is another research initiative aiming to study blockchains and their social, economic, and political effects on individuals, organisations and communities. [245]. Leading supporters include Endesa (part of Enel Group), who have launched a blockchain startup competition, aiming to identify new business opportunities for blockchain technologies in the energy sector [246].

In Spain, Alastria represents a national blockchain initiative across different sectors that aims to develop a semi-public distributed ledger technologies infrastructure and a collaborative multipartner digital platform that will be compliant with Spanish and EU regulatory and legal frameworks [247]. Alastria comprises some of the largest banking institutions, communication firms, energy companies, governing and research institutions across Spain.

In the Netherlands, BlockLab is a funding initiative from the City of Rotterdam and Port of Rotterdam, also supported by governing and academic partners. BlockLab has provided funding for pilot projects that aim to examine the feasibility of blockchain technologies for logistics and energy applications. Four blockchain pilot projects have been supported by the initiative [248]. Finally, the European Commission has announced the creation of the EU Blockchain Observatory and Forum that aims to facilitate the adoption of blockchain technologies in the EU [249].

5. Discussion of key challenges and future outlook

The blockchain projects and research initiatives reviewed in this work show that blockchains are a promising technology for a wide area of services and use cases in the energy sector. The large number of established energy companies and utilities that are currently involved in DLT projects, as well as the investor interest in this area, clearly shows the potential value of this emerging technology for the energy industry. The real, long-term value is, however, yet to be proven, especially as most initiatives have trialled the technology in relatively small-scale projects that are still in an early development phase. As a result, several questions will need to be answered before mainstream adoption of the blockchains in the energy industry.

First and foremost, blockchain technologies need to prove they can offer the scalability, speed and security required for the proposed use cases. Research efforts on distributed consensus algorithms, which are crucial to achieving these objectives, are still ongoing, however a solution that combines all desired characteristics cannot yet be achieved without significant trade-offs. PoW algorithms are more mature and secure, but on the other hand are also slow and very energy intensive. As a result, blockchain developers are increasingly moving towards PoS schemes that are energy efficient, faster and more scalable. Other promising solutions include techniques such as 'sharding' that enable parallel processing. Often these solutions may come, however, to the expense of security and decentralisation. Early adopters of blockchain technologies face the challenge of selecting the right consensus mechanism and system architecture, without having a clear long-term picture of the advantages and downsides that each approach has to offer.

Hence, it is clear that blockchain technologies have already passed the proof of concept stage for several use cases but require further development to achieve desired operational and performance objectives. Several recent developments, such as the Energy Web blockchain, can be scaled up to thousands of transactions per second. Similar future developments will significantly determine blockchain adoption in several applications, such as for IoT platforms and services that require very fast confirmation and large numbers of transactions.

Resilience to security risks stemming from unintentionally bad system design or malicious attacks are highly likely. Blockchains face additional risks such as possible malfunctions at early stages of development due to lack of experience with large-scale applications. Blockchain ecosystems rely heavily on coding new algorithms, a procedure that can be prone to errors. Security breaches are still highly likely before the technology becomes mature, which could result in bad publicity and delays in acceptance from consumers. With respect to cyber-attacks, Bitcoin, the oldest blockchain implementation, has proved to be relatively resilient, but other platforms such as Ethereum, have been the target of serious attacks in the past. Crucially, vulnerabilities in terms of cyber-security often come from peripheral applications, such as digital wallets or smart contracts. Resilience to such attacks is of great importance, especially for applications in critical infrastructure, such as energy systems.

Another important challenge is that blockchain systems have currently high development costs [43]. Blockchains may realise significant cost savings by circumventing intermediaries, however for several use cases, they might not have the competitive advantage against already existing solutions in well-established markets. For example, energy transactions can be recorded in conventional databases, such as relational databases that are designed to recognise relations between stored items of information [83]. These solutions are already largely available and currently faster and less costly to operate [21], albeit they cannot offer immutability of records or transparency. Blockchain systems may require costly new infrastructure, such as custom ICT equipment and software, the costs of which need to be outweighed by benefits achieved by data integrity, enhanced security and elimination of the need for a trusted intermediary. In the energy sector, smart meters are currently being rolled out without significant computational capabilities, hence integrating the existing smart metering and grid infrastructure with distributed ledgers could come with significant costs.

At present, information in blockchain systems can be transferred for very low costs, but validation and verification of data comes with high hardware and energy costs [21]. Proof of stake or proof of authority algorithms may significantly improve this in the future. In the field of grid communications however, blockchain systems would need to compete with already established solutions such as telemetry, which is not only more mature, but also significantly cheaper technology solution [43]. Adding to the cost of information verification, blockchain systems also face an additional cost of storing the data in continuously expanding ledgers. Promising solutions proposed to address this challenge is storing actual data in 'sidechains' and operating the blockchain as a control layer rather than as a storage layer.

Significant barriers in the adoption of the technology are relevant both to the regulatory and legal sphere. Regulatory bodies endorse the active participation of consumers in electricity markets [6,22]. In addition, several policy makers have established supportive measures for local or community energy systems that aim to reduce costs for consumers, promote low-carbon technologies and tackle fuel poverty. Blockchain technologies can support or accelerate such objectives, therefore coordinate well with current regulatory priorities, however regulatory frameworks would need to be amended to allow larger adoption of DLT. For instance, in general lines current regulatory frameworks do not allow consumer to consumer electricity trading, such as in several P2P energy trading projects. New contract types will be required to describe agreements between prosumers and consumers, especially when counterparties make use of the public grid [21]. Most importantly, a new framework would be require new and potentially more flexible electricity tariffs, which are currently heavily regulated. In general, local or microgrid energy markets would need to be integrated with current regulatory practice.

P2P trading platforms are in early stages of development, therefore the scale of their adoption is currently limited. However, they have the potential to radically change established roles of incumbent energy companies, such as energy suppliers or grid operators, who are in most countries are regulated monopolies and own the physical infrastructure. In fact, regulatory bodies have granted special permission to pilot projects trialling such novel marketplaces to examine potential benefits for consumers and energy system operation. Blockchain technologies have started to prove their potential in decentralised microgrids, however they face challenges in balancing, integration with central controls, and coordination with the main grid. Energy trading needs to be reconciled with the system operator practice, and continuous decentralisation may lead to more complex management of energy systems overall. P2P marketplaces and local microgrids may even accelerate grid defection or lead to severe underutilisation of network assets. Such results would call for radical changes in the way network charges and energy services are offered to consumers. In the case of P2P platforms granting access of consumers to wholesale energy markets, DSO coordination of marketplaces might deliver greater benefits for the consumer, according to a report from Eurelectric [43]. All these issues call for significant regulatory changes and might lead to delays or lack of blockchain adoption.

In addition, regulatory authorities are responsible for setting the rules of consumer data protection. A recent example is the new EU policy on consumer data or GDPR. Blockchain system users should be identified to account for their liabilities but at the same time, consumer or commercial sensitive information need to remain confidential, such as the prices agreed between an energy supplier and consumer within a smart contract recorded in a ledger. When information from multiple participants are recorded in shared ledgers, solutions need to be found for data privacy, confidentiality and identity management. Moreover, smart contracts need to be integrated into legal code to ensure compliance with the law and protection of consumers. In a distributed system architecture, it is not always clear who has the legal and technical responsibility for the negative consequences of the actions of different parties. For instance, if a major attack is successfully deployed because of a software or a hardware bug in the system, there is no central authority to which a consumer may address their complaints to, as in current practice. With blockchain systems, trust is put to the technology itself rather than in a known authority.

Finally, another significant factor that might slow blockchain adoption is the lack of standardisation and flexibility. Standards for blockchain architectures need to be developed to allow interoperability between technology solutions. An additional challenge is that once a blockchain system is deployed, any changes in the ruling protocols or code needs to be approved by the system nodes. In blockchain ecosystems, this has historically led to disagreements between developers and multiple system forks. If blockchains are largely adopted in energy systems, these issues may lead to mistrust and fragmentation [43]. Moreover, blockchain adoption might, in some cases, be inhibited by the bad reputation stemming from the early days of Bitcoin and its association with illegal activities - although as blockchains mature, this aspect may become less relevant over time.

6. Conclusions

To conclude, blockchain or distributed ledger technologies can clearly benefit energy system operations, markets and consumers. They offer disintermediation, transparency and tamper-proof transactions, but most importantly, blockchains offer novel solutions for empowering consumers and small renewable generators to play a more active role in the energy market and monetise their assets. Blockchains have enabled applications of sharing-economy in the energy sector, which has prompted several authors to speak about novel market models and energy democratisation [79]. Many research and commercial parties are currently pursuing blockchain innovation in the energy sector. Blockchains are a fast-moving area of research and development, therefore a review on this emergent technology is required to improve understanding, inform the body of knowledge on blockchains and realise their potential.

The contribution of this work is to provide a timely, academic-led review on DLT in the energy sector. First, this paper reviewed various academic and industrial sources, and presented an overview on the fundamentals of blockchain technologies, including system architectures and distributed consensus algorithms, critical components of performance for blockchain ecosystems. Next, the paper presented several energy use cases along with an in-depth discussion on benefits and issues blockchain solutions are facing for each application. Next, we provided a systematic review on a broad range of blockchain activities that showcased the specific areas in which energy system stakeholders and industrial parties are pursuing innovation. Our work shows that most projects are in an early development phase, and research is still ongoing on key improvement areas that would allow desired scalability, decentralisation and security. Blockchain technologies can be disruptive for energy companies and face a large variety of challenges to achieve market penetration, including legal, regulatory and competition barriers. Additional research initiatives, trials, projects and collaborations will show if the technology can reach its full potential, prove its commercial viability and finally be adopted in the mainstream.

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Appendix A

See Table A1.

Table A1
Summarised projects used in our survey.

#	Company & project	Field of activity	Platform	Consensus algorithm	Location
1	4New	Cryptocurrencies, tokens & investment	n/a	n/a	UK
2	Alastria	General purpose initiatives & consortia	n/a	n/a	Spain
3	Alliander & Spectral Energy (Jouliette at De Ceuvel)	Decentralised energy trading	MultiChain	Proof of Work, Round Robin-based	Netherlands
4	Alliander (Alva)	Decentralised energy trading	Ethereum	Proof of Work	Netherlands
5	Alliander (Charge Ledger)	Electric e-mobility	Ethereum	Proof of Work	Netherlands
6	Assetron Energy	Cryptocurrencies, tokens & investment	Waves	n/a	Australia
7	Bankymoon	Metering, billing & security	Ethereum	Proof of Work	South Africa
8	BAS Nederland	Metering, billing & security	n/a	n/a	Netherlands
9	BCDC (Blockchain Development Company)	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	UK
10	BCPG Group	Decentralised energy trading	n/a	n/a	Thailand
11	Bittwatt	Decentralised energy trading	Ethereum	n/a	Romania
12	BLOC (EnergyBlock & Community Power)	Decentralised energy trading	n/a	n/a	Denmark
13	Blockchain Futures Lab	General purpose initiatives & consortia	n/a	n/a	US
14	Blockchain Research Lab	General purpose initiatives & consortia	n/a	n/a	n/a
15	BlockLab	General purpose initiatives & consortia	n/a	n/a	Netherlands
16	Bouygues Immobilier & Stratumn	Decentralised energy trading	Proprietary	Proof of Process	France
17	BTL	Decentralised energy trading	Interbit	BFT-based	Canada & UK
18	Car eWallet	Electric e-mobility	Hyperledger Fabric	Practical Byzantine Fault Tolerance	Germany
19	CarbonX	Green certificates & carbon trading	Ethereum	Proof of Work	Canada
20	CGI & Eneco	Metering, billing & security	Tendermint	Practical Byzantine Fault Tolerance	Netherlands
21	Clearwatts	Decentralised energy trading	BigchainDB (Tendermint-based)	Practical Byzantine Fault Tolerance	Netherlands
22	Conjoule	Decentralised energy trading	Ethereum	Proof of Work	Germany
23	CoSol	Decentralised energy trading	Ethereum	Proof of Work	Brazil
24	DAISEE	IoT, smart devices, automation & asset management	Ethereum	Proof of Work	France
25	Dajie	IoT, smart devices, automation & asset management	n/a	n/a	UK
26	DAO IPCI (MITO)	Green certificates & carbon trading	Ethereum	Proof of Work	Russia
27	Department of Energy, US	Metering, billing & security	Keyless signature infrastructure (KSI)	n/a	US
28	Department of Energy, US	IoT, smart devices, automation & asset management	n/a	n/a	US
29	Divvi	Decentralised energy trading	Ethereum	Proof of Work	Australia
30	Dooak	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	Brazil
31	Drift	Decentralised energy trading	n/a	n/a	US
32	EcoCoin	Cryptocurrencies, tokens & investment	Hyperledger Fabric	Practical Byzantine Fault Tolerance	Netherlands
33	ElectriCChain (SolarCoin)	IoT, smart devices, automation & asset management	Bitseed, Chain of Things, Ethereum, Grid Singularity, IOTA and SolarCoin	n/a	Andorra
34	Electrify.Asia	Decentralised energy trading	Ethereum	n/a	Singapore
35	Electron	Metering, billing & security	Ethereum, Energy Web (Ethereum-based)	Proof of Work, Proof of Authority	UK
36	Electron	Grid management	Ethereum, Energy Web (Ethereum-based)	Proof of Work, Proof of Authority	UK
37	Elegant	Metering, billing & security	n/a	n/a	Belgium
38	eMotorwerks	Electric e-mobility	Ethereum	Proof of Work	US
39	Endesa Energia (Blockchain Lab)	General purpose initiatives & consortia	n/a	n/a	Spain
40	Enercity	Metering, billing & security	Tendermint	Practical Byzantine Fault Tolerance	Germany
41	Eneres	Decentralised energy trading	n/a	n/a	Japan
42	Energi Mine	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	UK
43	Energo Labs	Decentralised energy trading	Qtum	Proof of Stake (public Qtum), Proof of Time & Raft agreement (consortium Qtum)	China
44	Energo Labs	Electric e-mobility	Qtum	Proof of Stake (public Qtum), Proof of Time & Raft agreement (consortium Qtum)	China
45	Energy Bazaar	Decentralised energy trading	Ethereum	Proof of Work	India
46	Energy Web Foundation	General purpose initiatives & consortia	Energy Web (Ethereum-based)	Proof of Authority	Switzerland
47	Energy21 & Stedin	Decentralised energy trading	Quasar	n/a	Netherlands
48	Energy-Blockchain Lab & IBM	Green certificates & carbon trading	Hyperledger Fabric	Practical Byzantine Fault Tolerance	China

(*continued on next page*)

Table A1 (*continued*)

#	Company & project	Field of activity	Platform	Consensus algorithm	Location
49	Enervalis (NRGCoin)	Cryptocurrencies, tokens & investment	n/a	n/a	Belgium
50	Engie	Metering, billing & security	n/a	n/a	France
51	EnLedger	Cryptocurrencies, tokens & investment	Tendermint-based	Delegated Proof of Stake	US
52	Envion	Cryptocurrencies, tokens & investment	Tendermint-based	Delegated Proof of Stake	Germany
53	EU Blockchain Observatory and Forum	General purpose initiatives & consortia	n/a	n/a	EU
54	Eurelectric (Blockchain Discussion Platform)	General purpose initiatives & consortia	n/a	n/a	EU
55	EverGreenCoin	Cryptocurrencies, tokens & investment	n/a	n/a	US
56	Everty	Electric e-mobility	Ethereum	Proof of Work	Australia
57	Evolve Power	Grid management	Energy Web (Ethereum-based)	Proof of Authority	US
58	Farad	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	UAE
59	Filament	Grid management	Proprietary, Hyperledger Sawtooth	n/a, Proof of Elapsed Time	US
60	Filament	IoT, smart devices, automation & asset management	Proprietary, Hyperledger Sawtooth	n/a, Proof of Elapsed Time	US
61	Fortum	IoT, smart devices, automation & asset management	n/a	n/a	Finland
62	Freeelio (AdptEVE)	IoT, smart devices, automation & asset management	Energy Web (Ethereum-based)	Proof of Authority	Germany
63	Green Energy Wallet	Cryptocurrencies, tokens & investment	n/a	n/a	Germany
64	Green Running (Verv)	IoT, smart devices, automation & asset management	Energy Web (Ethereum-based)	Proof of Authority	UK
65	Green Running (Verv)	Decentralised energy trading	Energy Web (Ethereum-based)	Proof of Authority	UK
66	Greeneum	Decentralised energy trading	Ethereum	Proof of Work	Israel
67	Greeneum	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	Israel
68	Grid Singularity	Green certificates & carbon trading	Energy Web (Ethereum-based)	Proof of Authority	Austria
69	Grid Singularity	Grid management	Energy Web (Ethereum-based)	Proof of Authority	Austria
70	Grid+	Decentralised energy trading	Ethereum	Proof of Work	US
71	Grünstromjeton	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	Germany
72	Hive Power	Decentralised energy trading	Ethereum	Proof of Work	Switzerland
73	HydroMiner	Cryptocurrencies, tokens & investment	n/a	n/a	Austria
74	IBM & Linux Foundation (Hyperledger)	General purpose initiatives & consortia	Hyperledger Fabric, Hyperledger Sawtooth	Practical Byzantine Fault Tolerance, Proof of Elapsed Time	US
75	ImpactPPA	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	US
76	Innogy Motionwerk (Share&Charge)	Electric e-mobility	Ethereum, Energy Web (Ethereum-based)	Proof of Work, Proof of Authority	Germany
77	Intrinsic ID & Guardtime	IoT, smart devices, automation & asset management	Keyless signature infrastructure (KSI)	n/a	US
78	Inuk	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	France
79	KEPCO	Decentralised energy trading	Ethereum	Proof of Work	Japan
80	LO3 Energy	Decentralised energy trading	Tendermint, Proprietary	n/a, Practical Byzantine Fault Tolerance	US
81	Local-e	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	US
82	Marubeni (Coincheck Denki)	Metering, billing & security	Hyperledger Fabric	Practical Byzantine Fault Tolerance	Japan
83	M-PAYG	Metering, billing & security	n/a	n/a	Denmark
84	MyBit	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	Switzerland
85	Nasdaq New York Linq	Green certificates & carbon trading	Chain	Federated Byzantine Agreement	US
86	Oli	IoT, smart devices, automation & asset management	Ethereum	n/a	Germany
87	OMEGAGrid	Decentralised energy trading	n/a	n/a	US
88	OneUp	Decentralised energy trading	Ethereum	Proof of Work	Netherlands
89	OurPower (CEDISON)	Grid management	n/a	n/a	UK
90	Oursolargrid & ITP	Decentralised energy trading	Ethereum	Proof of Work	Germany
91	Oxygen Initiative	Electric e-mobility	Ethereum	Proof of Work	US
92	PetroBloq	Decentralised energy trading	n/a	n/a	Canada
93	Platinum Energy Recovery	Decentralised energy trading	n/a	n/a	Singapore
94	PONTON (EnerChain)	Decentralised energy trading	Tendermint	Practical Byzantine Fault Tolerance	Germany
95	PONTON (GridChain)	Grid management	Tendermint	Practical Byzantine Fault Tolerance	Germany
96	Poseidon	Green certificates & carbon trading	Stellar	Federated Byzantine Agreement	Switzerland

(*continued on next page*)

Table A1 (*continued*)

#	Company & project	Field of activity	Platform	Consensus algorithm	Location
97	Power Ledger (EcoChain)	Decentralised energy trading	Ethereum	Proof of Work	Australia
98	Power Ledger	IoT, smart devices, automation & asset management	Ethereum	Proof of Work	Australia
99	Power Ledger	Electric e-mobility	Ethereum	Proof of Work	Australia
100	Power Ledger	Green certificates & carbon trading	Ethereum	Proof of Work	Australia
101	Power Ledger	Grid management	Ethereum	Proof of Work	Australia
102	Power-ID	Decentralised energy trading	n/a	n/a	Switzerland
103	PROSUME	Metering, billing & security	Proprietary	n/a	Switzerland
104	PROSUME	Cryptocurrencies, tokens & investment	Proprietary	n/a	Switzerland
105	PROSUME	Decentralised energy trading	Proprietary	n/a	Switzerland
106	PROSUME	Grid management	Proprietary	n/a	Switzerland
107	PROSUME	Electric e-mobility	Proprietary	n/a	Switzerland
108	PRTI	Cryptocurrencies, tokens & investment	n/a	n/a	US
109	Pylon Network	Metering, billing & security	Pylon Coin CORE (LiteCoin & CREAtivecoin-based)	Proof of Capacity	Spain
110	Pylon Network	Decentralised energy trading	n/a	n/a	Spain
111	Restart Energy	Decentralised energy trading	Pylon Coin CORE (LiteCoin & CREAtivecoin-based)	Proof of Capacity	Romania
112	Slock.it	IoT, smart devices, automation & asset management	Ethereum, Energy Web (Ethereum-based)	Proof of Work, Proof of Authority	Germany
113	Slock.it	Electric e-mobility	Ethereum, Energy Web (Ethereum-based)	Proof of Work, Proof of Authority	Germany
114	Solar bankers (SunCoin)	Decentralised energy trading	Skycoin	Web of trust	Singapore
115	Solar DAO	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	Israel
116	SolarChange (SolarCoin)	Cryptocurrencies, tokens & investment	SolarCoin (LiteCoin & Vericoin-based)	Proof of Stake Time	Andorra
117	SP Energy Networks, SSEN, SP Distribution, SP Manweb & UK Power Networks	Grid management	n/a	n/a	UK
118	Spectral Energy	Decentralised energy trading	MultiChain	Proof of Work, Round Robin-based	Netherlands
119	StromDAO	Decentralised energy trading	Fury Network	Proof of Authority	Germany
120	SunChain (TECSOL & Enedis)	Metering, billing & security	Hyperledger Fabric	Practical Byzantine Fault Tolerance	France
121	SunContract	Decentralised energy trading	n/a	n/a	Slovenia
122	Swytch	IoT, smart devices, automation & asset management	n/a	n/a	South Korea
123	Tavrida Electric	IoT, smart devices, automation & asset management	n/a	n/a	Russia
124	Tennet & Sonnen	Grid management	Hyperledger Fabric	Practical Byzantine Fault Tolerance	Netherlands
125	Tennet & Vandenbron	Grid management	Hyperledger Fabric	Practical Byzantine Fault Tolerance	Netherlands
126	The Sun Exchange	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	South Africa
127	ToBlockChain	Decentralised energy trading	n/a	n/a	Netherlands
128	toomuch.energy	Decentralised energy trading	n/a	n/a	Belgium
129	VAKT & partners (including BP, Shell & Statoil)	Decentralised energy trading	n/a	n/a	UK
130	Vattenfall (Powerpeers)	Decentralised energy trading	n/a	n/a	Netherlands
131	Vector Energy (EcoChain)	Decentralised energy trading	Ethereum	Proof of Work	New Zealand
132	Veridium Labs	Green certificates & carbon trading	Ethereum	Proof of Work	Hong Kong
133	Volts Markets	Decentralised energy trading	Ethereum	Proof of Work	US
134	Volts Markets	Green certificates & carbon trading	Ethereum	Proof of Work	US
135	Wanxiang	IoT, smart devices, automation & asset management	Ethereum	Proof of Work	China
136	WePower	Cryptocurrencies, tokens & investment	Ethereum	Proof of Work	Gibraltar
137	Wien Energie	Decentralised energy trading	Interbit	n/a	Austria
138	Wirepas	IoT, smart devices, automation & asset management	Energy Web (Ethereum-based)	Proof of Authority	Finland
139	Wuppertal Stadtwerke (Tal.Markt)	Decentralised energy trading	n/a	n/a	Germany
140	XinFin	Cryptocurrencies, tokens & investment	Proprietary	n/a	Singapore

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