Blockchain in Electricity: a Critical Review of Progress to Date

DISCLAIMER

This report has been drafted by NERA Economic Consulting in close liaison with Zdenek Pekarek and members of Eurelectric's Blockchain discussion platform. It aims at taking stock of current developments with regard to the blockchain technology, as one of the various possible digital solutions in developing the future energy system. In so doing, the report aims at mapping out the challenges and opportunities linked to the use of this technology. Through this report, the Eurelectric Blockchain platform seeks to initiate further, long-term debates on the role of blockchain and other distributed ledger technologies in the future energy sector. The report provides a preliminary, fact-based, assessment of existing initiatives which allow the forward-looking energy consumers and utilities to better understand and navigate the potential offered by blockchain technology.

The report does not represent a formal Eurelectric position and should be treated as a White Paper, marking the direction and scope of future work on the topic.

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May 2018

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1. Introduction

The past year saw a marked increase in the global recognition of blockchain technology and its potential applications. The price of Bitcoin—the first and most widely-used blockchain-based cryptocurrency—increased to a peak value that was twenty times higher than its value at the beginning of the year. The number of projects using the Ethereum blockchain platform—designed to feature "smart contract" functionality—increased to well over 1,000.[1] Furthermore, Initial Coin Offerings (ICOs) gained traction as an alternative to traditional venture capital funding: there were 210 ICOs in 2017 (compared to just 46 in 2016) that together generated more than €3 billion. In the first quarter of 2018, 166 ICOs generated €4.8 billion.[2]

Blockchains have gained attention in academia and industry because of a core innovation: they help to guarantee the validity of a transaction by recording it not only on a main register but on a distributed system of registers, all of which are connected through a secure validation mechanism. Blockchain technology offers a way for untrusted parties to reach agreement on a common digital record that might otherwise be easily faked or duplicated. It achieves this without using trusted intermediaries.

Blockchain technology has the potential to be most immediately useful in sectors where there is no physical exchange, such as in the financial, banking, and insurance sectors.[3] In such sectors, blockchains can provide credible records of transactions without the need for verification of physical exchange. Of the sectors with physical exchange, however, the electricity sector is perhaps more susceptible than others to the integration of blockchain technology. Electricity travels at the speed of light and cannot be tracked between two points in an electricity network. Because of this, electricity markets are pooled—that is, electricity sales and purchases are cleared in aggregate on centralised trading platforms similar to stock exchanges and other financial market platforms.

Recognising blockchain technology's potential value in the electricity sector, many companies and consortia are investing and are actively

EARLY BLOCKCHAIN-BASED ENERGY TRANSACTIONS WERE TAKING PLACE BY 2014. BY MARCH 2018, THERE WERE 122 ENERGY SECTOR ORGANISATIONS INVOLVED IN BLOCKCHAIN TECHNOLOGY AND 40 PUBLICLY ANNOUNCED DEPLOYED PROJECTS. BETWEEN THE SECOND QUARTER OF 2017 AND THE FIRST QUARTER OF 2018, A COMBINATION OF VENTURE CAPITAL AND ICOS INVESTED OVER €240 MILLION IN BLOCKCHAIN-BASED ENERGY PROJECTS (WITH ICOS MAKING UP 75 PERCENT OF THE TOTAL).

1 State of the ÐApps, https://www.stateofthedapps.com/ (last accessed April 24, 2018).
2 CoinSchedule, https://www.coinschedule.com/stats.html (last accessed April 24, 2018).
3 Indeed, those three industries comprise about half of all blockchain projects. See Hileman, G. and M. Rauchs, "Global Blockchain Benchmarking Study," Cambridge Centre for Alternative Finance, University of Cambridge Judge Business School, 2017.

involved in blockchain-related projects. Early blockchain-based energy transactions were taking place by 2014.[4] By March 2018, there were 122 energy sector organisations involved in blockchain technology and 40 publicly announced deployed projects. Between the second quarter of 2017 and the first quarter of 2018, a combination of venture capital and ICOs invested over €240 million in blockchain-based energy projects (with ICOs making up 75 percent of the total).[5] Active projects seek to add value to wholesale and retail electricity markets, peer-to-peer energy marketplaces, the provision of "flexibility" or balancing services, electric vehicle charging and coordination, network security, and markets for environmental attributes (such as renewable energy and carbon emission certificates).

Despite its potential value, however, blockchain's future in electricity systems is uncertain. Blockchains represent new technologies with no scaled commercial projects in the electricity industry. The technology class is currently burdened by high costs, slow transaction speeds, and other limitations and risks. Unique characteristics of the electric power sector—such as the presence of economies of scale and scope in network operation—challenge the ability of certain blockchain-based applications to scale. Moreover, blockchain technologies face competitive pressures and public perception challenges.

This paper discusses current blockchain-related activities and critically assesses the potential for growth of blockchain technologies in the electricity sector. Section 2 introduces some characteristics of the technology. Section 3 discusses blockchain's potential in the electricity sector. The section first summarises the technology's oft-cited value propositions and provides examples of active blockchain projects in the electricity sector. It then discusses some of the limitations, risks, and challenges facing the technology. Section 4 concludes and summarises the findings of the paper. This paper draws extensively upon the input of eurelectric Blockchain Discussion Platform members representing 25 European utilities.

4 Macheel, T., "Bitcoin Smart Meters Could Revolutionise How South Africans Pay for Power," CoinDesk, June 3, 2014 (updated June 27, 2014).
5 Metelitsa, C., "Blockchain for Energy 2018: Companies & Applications for Distributed Ledger Technologies on the Grid," GTM Research, March 2018.

2. What is a Blockchain?

A blockchain is a list of records, or "blocks," that are linked to one another and cryptographically secured. Participants in a blockchain network have records of every transaction and these records are stored locally on the computers of all participants in that blockchain network. Any kind of regime or protocol change to a blockchain network requires consensus between the users of the network.

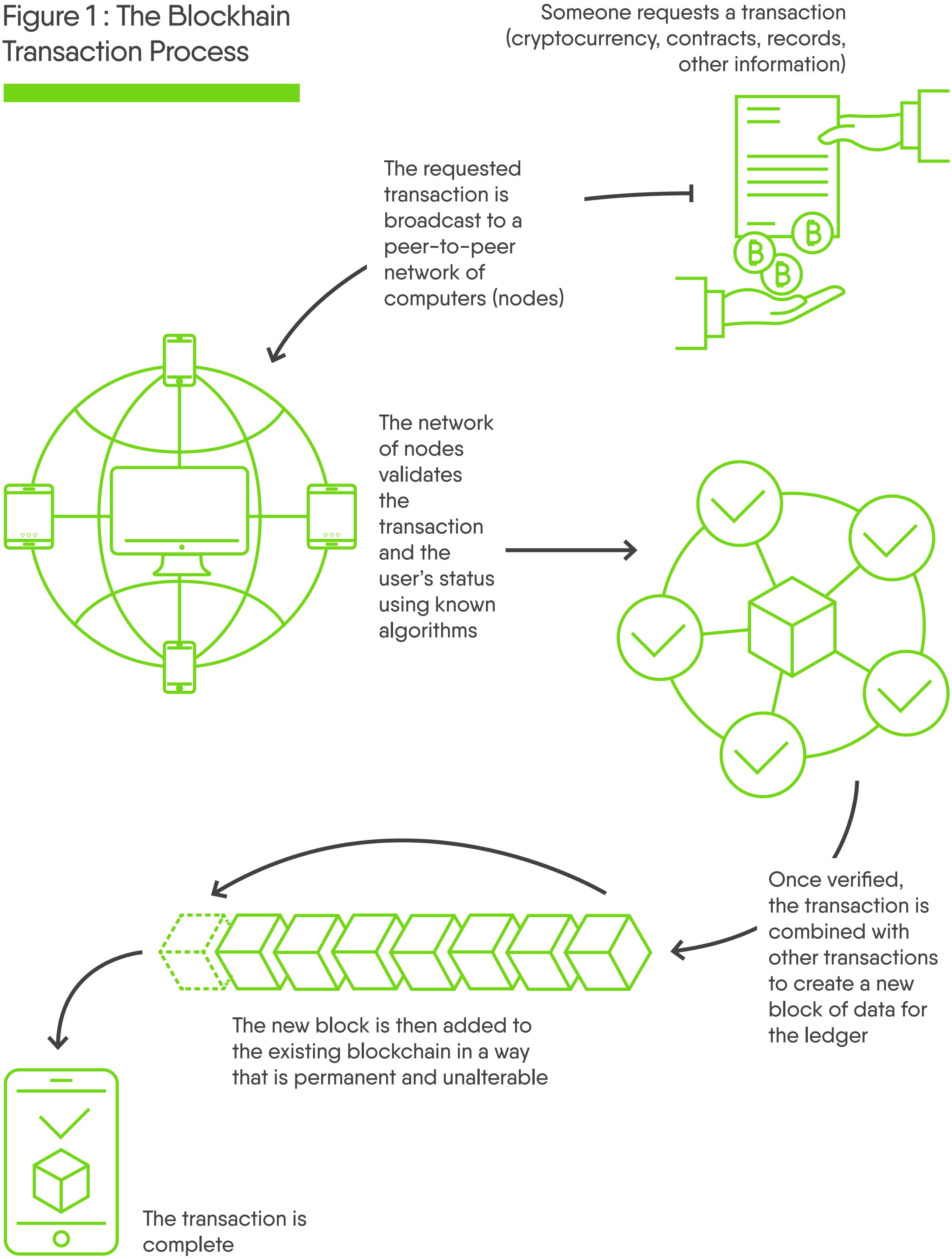
Figure 1 illustrates a typical blockchain transaction process. The process begins when a blockchain network user requests a transaction—whether it be a transaction related to cryptocurrency, a contract, record, or other information. The transaction is broadcast to a peer-to-peer network of computers (nodes). The network of nodes then verifies the transaction using known algorithms that attach a unique "hash" to the transaction.[6] Once verified, the transaction is combined with other transactions to create a block of data for the ledger. The new block is then added to the existing blockchain in a way that is permanent and unalterable.

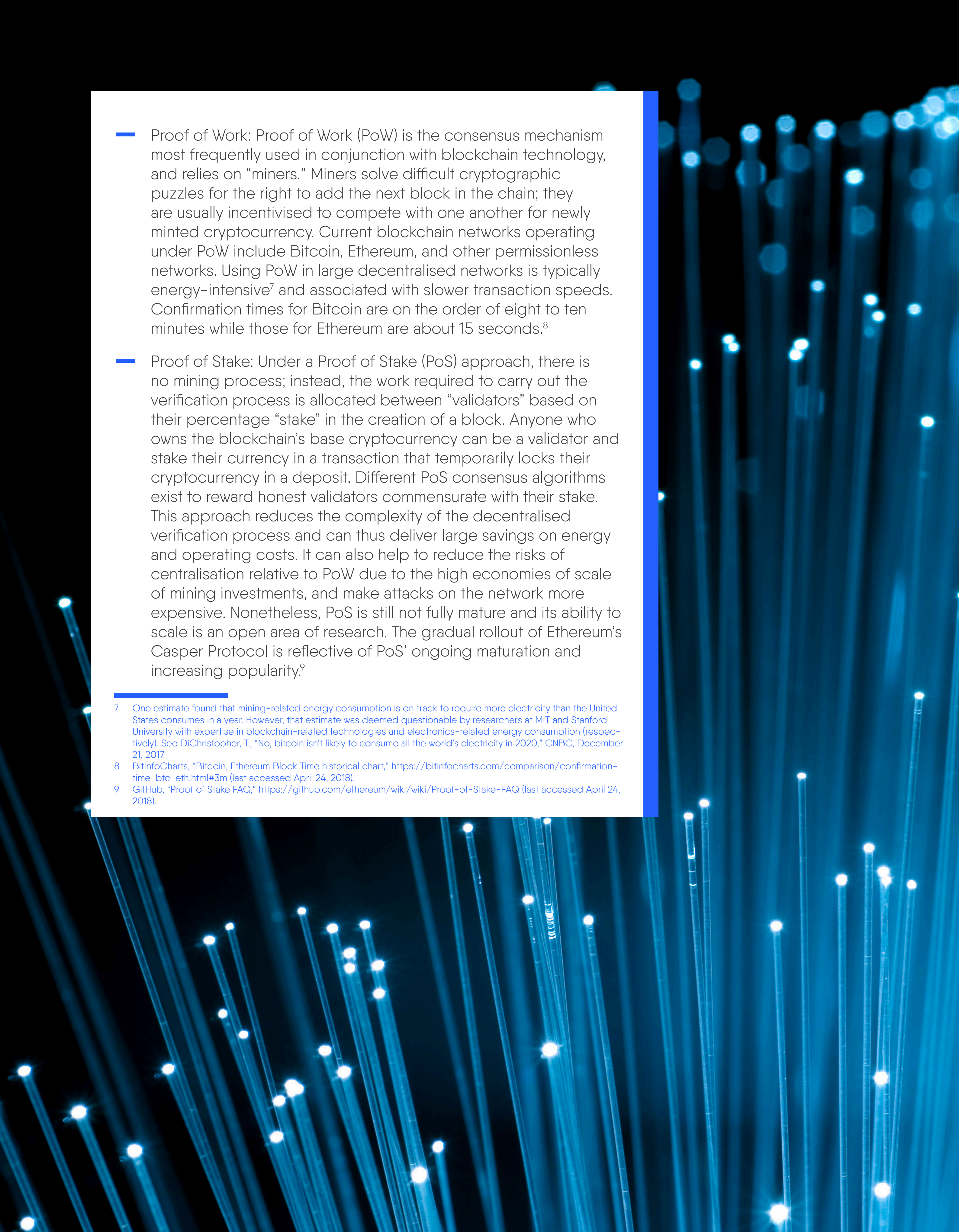
The process by which distributed operators of a blockchain verify transactions before they are permanently incorporated into the blockchain, is called "consensus." Achieving consensus allows a blockchain to grow while preventing adversarial agents from manipulating and "forking" the chain in a different direction. Since blocks represent sets of transactions (or sets of data to be added to the ledger) and are verified through the consensus process in discrete time intervals, there is generally a duration for transaction confirmation between the time a transaction takes place and the addition of that transaction to the blockchain via a block. Average confirmation times reflect transaction volumes, block sizes, and consensus algorithms. Correspondingly, different consensus algorithms with different properties are used or are under development; four common variations, "Proof of Work," "Proof of Stake," "Proof of Authority," and "Practical Byzantine Fault Tolerance," are discussed in Box 1. There are trade-offs between these four variations with respect to stakeholder roles, transaction throughput, information security, barriers to entry, and energy consumption.

A BLOCKCHAIN IS A LIST OF RECORDS, OR "BLOCKS," THAT ARE LINKED TO ONE ANOTHER AND CRYPTOGRAPHICALLY SECURED. PARTICIPANTS IN A BLOCKCHAIN NETWORK HAVE RECORDS OF EVERY TRANSACTION AND THESE RECORDS ARE STORED LOCALLY ON THE COMPUTERS OF ALL PARTICIPANTS IN THAT BLOCKCHAIN NETWORK.

6 A hash is an alphanumeric that corresponds to a particular blockchain transaction. Bitcoin, for instance, uses an algorithm (Secure Hashing Algorithm 256) to convert each Bitcoin transaction into a character string with a fixed 256-bit (64 character) length.

Figure 1 : The Blockchain Transaction Process





- Proof of Work: Proof of Work (PoW) is the consensus mechanism most frequently used in conjunction with blockchain technology, and relies on "miners." Miners solve difficult cryptographic puzzles for the right to add the next block in the chain; they are usually incentivised to compete with one another for newly minted cryptocurrency. Current blockchain networks operating under PoW include Bitcoin, Ethereum, and other permissionless networks. Using PoW in large decentralised networks is typically energy-intensive[7] and associated with slower transaction speeds. Confirmation times for Bitcoin are on the order of eight to ten minutes while those for Ethereum are about 15 seconds.[8]

- Proof of Stake: Under a Proof of Stake (PoS) approach, there is no mining process; instead, the work required to carry out the verification process is allocated between "validators" based on their percentage "stake" in the creation of a block. Anyone who owns the blockchain's base cryptocurrency can be a validator and stake their currency in a transaction that temporarily locks their cryptocurrency in a deposit. Different PoS consensus algorithms exist to reward honest validators commensurate with their stake. This approach reduces the complexity of the decentralised verification process and can thus deliver large savings on energy and operating costs. It can also help to reduce the risks of centralisation relative to PoW due to the high economies of scale of mining investments, and make attacks on the network more expensive. Nonetheless, PoS is still not fully mature and its ability to scale is an open area of research. The gradual rollout of Ethereum's Casper Protocol is reflective of PoS' ongoing maturation and increasing popularity.[9]

7 One estimate found that mining-related energy consumption is on track to require more electricity than the United States consumes in a year. However, that estimate was deemed questionable by researchers at MIT and Stanford University with expertise in blockchain-related technologies and electronics-related energy consumption (respectively). See DiChristopher, T., "No, bitcoin isn't likely to consume all the world's electricity in 2020," CNBC, December 21, 2017.

8 BitInfoCharts, "Bitcoin, Ethereum Block Time historical chart," https://bitinfocharts.com/comparison/confirmation-time-btc-eth.html#3m (last accessed April 24, 2018).

9 GitHub, "Proof of Stake FAQ," https://github.com/ethereum/wiki/wiki/Proof-of-Stake-FAQ (last accessed April 24, 2018).

- Proof of Authority: Under Proof of Authority (PoA), approved accounts or validators run software allowing them to place transactions in blocks. Although the process is automated and does not require validators to be constantly monitoring their computers, maintaining the security of PoA-based blockchains requires that validators' computers ("authority nodes") are uncompromised. The PoA approach is more centralised and prone to attack than the others but is associated with much faster transaction speeds. An example of a PoA-based network is the Tobalaba Energy Web Foundation test network whose validators include energy/electricity companies Shell, Engie, Statoil, Centrica, Tepco, and others.[10] That network has an average confirmation time of approximately three to four seconds.[11]

- Practical Byzantine Fault Tolerance: Blockchain aims to solve the so called "Byzantine Generals' Problem," a dilemma that arises when a group is trying to make a collective decision about how it will act, and faces a risk that traitors within the group may send mixed messages about their preferences.[12] In blockchain networks, if some members of the community send inconsistent information to others about transactions, the reliability of the blockchain breaks down, and there is no authority that can step in to correct it. The Practical Byzantine Fault Tolerance (PBFT) algorithm and variants seek to achieve consensus in the face of such "Byzantine faults." PBFT uses the concept of primary and secondary "replicas," where the secondary replicas automatically evaluate the decisions taken by the primary and can collectively switch to a new primary if the primary is found to be compromised.[13] Hyperledger, an open-source collaborative effort led the Linux Foundation, is an example of a project that relies on PBFT.

10 Energy Web Foundation, http://energyweb.org/network/ (last accessed April 24, 2018)
11 Energy Web Foundation, "Tobalaba Network Status," http://netstats.energyweb.org/ (last accessed April 24, 2018).
12 Lamport, L., Shostak, R., and M. Pease, "The Byzantine Generals Problem," ACM Transactions on Programming Languages and Systems, 4: 382-401 (1982).
13 Castro, M. and B. Liskov, "Practical Byzantine Fault Tolerance," Proceedings of the Third Symposium on Operating Systems Design and Implementation, New Orleans, United States, February 1999.

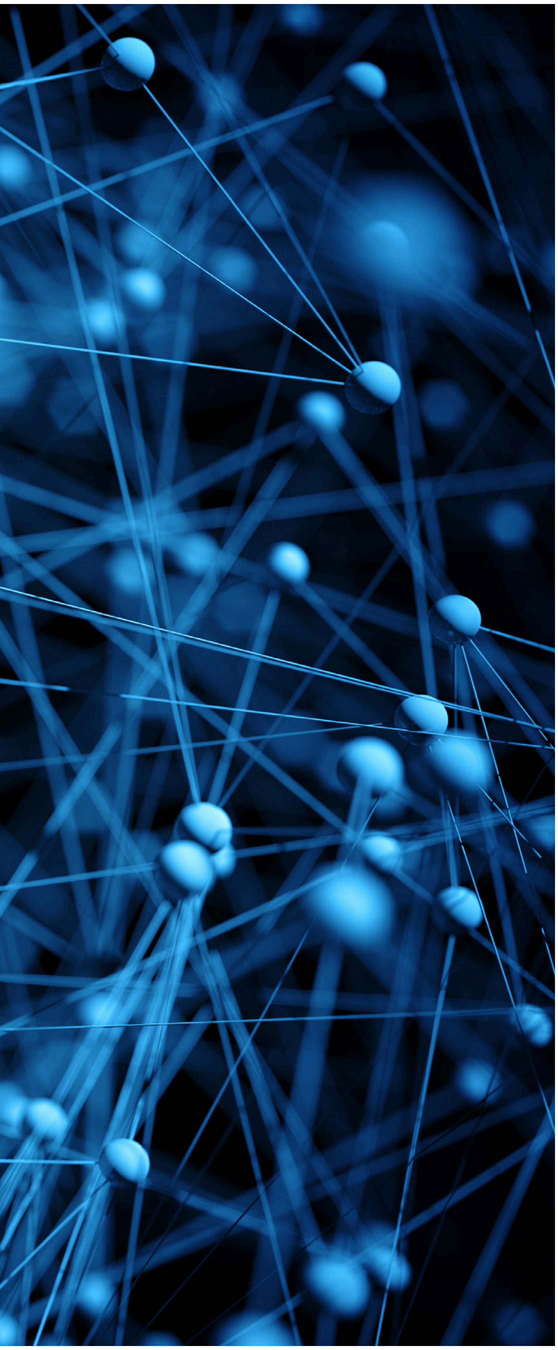
Apart from their consensus algorithms, blockchains can be distinguished from one another by their "permission models," which define the permissions types that may be given to network participants. "Public" and "private" blockchain designations refers to the "read" capability: who is or is not allowed to view transactions on the blockchain. Public blockchains are open to anyone while transactions on private blockchains are restricted to a subset of authorised participants. "Permissionless" and "permissioned" blockchains refer to the "write" and "commit" capabilities of blockchains: who can send transactions and perform verification, respectively. As their names imply, permissionless blockchains allow anyone to write and commit, while permissioned blockchains require authorisation.

Blockchains with a number of different technical system architectures and governance models are being tested, allowing for various speeds, costs, and degrees of "base-layer" decentralisation. The base-layer refers to the underlying blockchain, which can support distributed applications that themselves have myriad business models and subsequently enable varying degrees of transaction disintermediation. Table 1 summarises some of the technical and governance characteristics of public and private blockchains.

Table 1: Blockchains Have a Variety of Technical and Governance Characteristics

	PUBLIC	PRIVATE
Access right	Open, anyone can write/read	Restricted "Know Your Customer" (KYC) policy
Validation	Permissionless, unknown validators (risk of "Sybil attack")	Permissioned, known validators (can ban who misbehave)
Speed	Slow clearing, fast settlement	Fast, high performances. Settlement might be slow depending on the process
Security	Immutable record	Reversible, can edit and change the history
Identity	Anonymous/pseudonymous	Known (KYC rules)
Asset	Native digital token used for mining reward	Customisable type of asset
Cost	Energy, OPEX	Development cost, CAPEX
Consensus	Proof of Work, possible Proof of Stake in the future	Proof of Stake, Delegated Proof of Stake, Proof of Elapsed Time, Byzantine Fault Tolerance algorithms

A WELL KNOWN LIMITATION OF CURRENT PUBLIC BLOCKCHAINS IS THEIR LIMITED THROUGHPUT, I.E. NUMBER OF TRANSACTIONS PROCESSED PER SECOND. LIMITED THROUGHOUT HINDERS THE ABILITY FOR BLOCKCHAIN APPLICATIONS TO SCALE. METHODS FOR IMPROVING BLOCKCHAIN TRANSACTION THROUGHPUT SUCH AS “SHARDING” AND “SECOND-LAYER” PROTOCOLS ARE ACTIVE TOPICS OF RESEARCH.



A well known limitation of current public blockchains is their limited throughput, i.e. number of transactions processed per second. Limited throughout hinders the ability for blockchain applications to scale. Methods for improving blockchain transaction throughput such as “sharding” and “second-layer” protocols are active topics of research. Sharding involves the redesign of base-layer blockchain protocols so that only a small number of nodes need to process a given transaction; this promises to allow transactions to be processed in parallel across a network, increasing transaction speeds. Second-layer protocols, such as Bitcoin Lightning Network, involve sending some transactions “off-chain,” so that only aggregated transaction data incurs the cost of being recorded on the base-layer.[14] Implementing sharding and second layer protocols while maintaining the desirable security and decentralisation properties of public blockchains are ongoing challenges.

Blockchain applications can be divided into three broad categories based on their stages of complexity. “Blockchain 1.0” includes cryptocurrencies such as Bitcoin that can be used as alternatives to fiat currencies (e.g. the Euro or the U.S. Dollar) or to scarce physical assets. Bitcoin, for instance, achieves scarcity by nature of its fixed limited supply of 21 million bitcoins. “Blockchain 2.0” includes the use of “smart contracts,” which are digital protocols that automatically execute predefined processes of a transaction without necessitating the involvement of a centralised intermediate (e.g., automatic payment for electric car charging, etc.). Finally, “Blockchain 3.0” is the stage where the smart contract concept is developed further so as to create Decentralised Autonomous Organisations (DAO) that rely on their own laws (i.e. computer code) and operate with a high degree of autonomy. While systems based on Blockchain 1.0 and 2.0 are currently in use and show promise for additional near-term applications, initial Blockchain 3.0 systems have struggled to succeed. It is unlikely that Blockchain 3.0 applications will popularise until the software environment matures.

14 Buterin, V., “Ethereum scalability research and development subsidy programs,” Ethereum Blog, January 2, 2018.

3. The Potential for Blockchain in Electricity

Blockchain technology has the potential to be most immediately useful in sectors where there is no physical exchange, such as in the financial sector. In such sectors, blockchains can provide credible records of transactions without the need for verification of physical exchange. Of the sectors with physical exchange, however, the electricity sector is perhaps more susceptible than others to the integration of blockchain technology. Electricity sales and purchases are cleared in aggregate on centralised trading platforms similar to stock exchanges and other financial market platforms.

Recent years have seen the emergence of blockchain projects that seek to enhance electricity sector markets and operations. Today, there are more than 120 organisations involved in such projects and about 40 deployed pilot projects.[15] These projects hope to find application in wholesale and retail electricity markets, peer-to-peer energy marketplaces, the provision of "flexibility" or balancing services, electric vehicle charging and coordination, network security, and markets for environmental attributes (such as renewable energy and carbon emission certificates). These potential applications and project examples are discussed further in Section 3.1.

Despite its potential value, however, blockchain technology's future in electricity systems is uncertain. Blockchains represent new technologies with no scaled commercial projects in the electricity industry. The technology class remains burdened by high costs, slow transaction speeds, and other limitations and risks. Unique characteristics of the electric power sector—such as the presence of economies of scale and scope in network operation—challenge the ability of certain blockchain-based applications to scale. Moreover, blockchains face competitive pressures and public perception challenges. These limitations, risks, and challenges are discussed further in Section 3.2.

15 Metelitsa, C., March 2018.

BLOCKCHAIN TECHNOLOGY HAS THE POTENTIAL TO BE MOST IMMEDIATELY USEFUL IN SECTORS WHERE THERE IS NO PHYSICAL EXCHANGE, SUCH AS IN THE FINANCIAL SECTOR. IN SUCH SECTORS, BLOCKCHAINS CAN PROVIDE CREDIBLE RECORDS OF TRANSACTIONS WITHOUT THE NEED FOR VERIFICATION OF PHYSICAL EXCHANGE. OF THE SECTORS WITH PHYSICAL EXCHANGE, HOWEVER, THE ELECTRICITY SECTOR IS PERHAPS MORE SUSCEPTIBLE THAN OTHERS TO THE INTEGRATION OF BLOCKCHAIN TECHNOLOGY.

3.1 Potential applications and current projects

This section provides examples of active projects and discusses how blockchain technology is envisioned contributing to different segments of the electricity sector. The potential applications and projects reviewed in this section were selected based upon input from the eurelectric Blockchain Discussion Platform members. They illustrate how blockchain could add value to electricity customers (including DER providers) and network utilities (DSOs and TSOs). Table 2 summarises the potential applications and projects described in this section.

Table 2: Blockchain Projects Span the Electricity Sector

	OPPORTUNITY/ POTENTIAL BENEFIT	PROJECT EXAMPLES
Wholesale energy trading	– Reduce transaction costs in wholesale energy trading	– Enerchain (Ponton) – Interbit (BTL)
Retail electricity markets	– Reduce variable costs of retail payment processing and accounting – Greater transparency into billing – Fluid energy contract entry/exit – Greater customer choice of energy supply	– Drift – Grid+
Peer-to-peer marketplaces	– Relieve stress on transmission networks – Improve DER economics – Greater customer choice of energy supply	– Brooklyn Microgrid Project (LO3 Energy) – Jouliette (Alliander and Spectral) – Verbund and Salzburg AG
Flexibility services	– Improve TSO ability to balance supply and demand	– TenneT – Electron
Electric vehicle charging and coordination	– Improve DSO ability to coordinate electric vehicle load and discharge	– Share&Charge (MotionWerk) – eMotorWerks
Network management and security	– Improve DSO and TSO network management and security	– Keyless Signature Infrastructure (Guardtime)
Environmental attribute markets	– Improve efficiency and transparency of environmental attribute markets	– SolarCoin – Ideo CoLab

3.1.1 WHOLESALE ENERGY TRADING

In electricity (and gas) trading, trades are initiated on an online exchange, or via a broker, after the initiating trader consults an index agency to gather pricing intelligence. After closing the trade, both traders separately enter the transaction details in their respective IT systems (known as "energy trading and risk management" [ETRM] systems). Both parties' back offices retrieve the transaction details from their ETRM systems and exchange the data with each other, and/or with the broker, in order to confirm and reconcile the trade. This step is achieved either by automated confirmation systems, like EFETnet in Europe, or through traditional communication channels (emails, calls, fax) and spreadsheets. The trade is then settled physically through a TSO (or pipeline or shipment for gas). It is also settled financially through a clearinghouse or bank. Finally, both actors report the transaction details to the relevant auditors and regulators according to their obligations.

This process uses siloed IT systems and sometimes inefficient communications. It can result in high transaction costs (costly exchange and broker fees, pricing agencies, etc.) and operational costs (time-consuming reconciliation issues, costly back office processes, etc.). Blockchain technology could reduce the transaction costs for trading large volumes by making operational processes more efficient and by connecting the trading desks of all parties. Some envisage blockchain-based trading platforms eliminating the need for brokers and clearinghouses. Moreover, by reducing transaction costs, blockchain could enable participants to trade in smaller volumes.

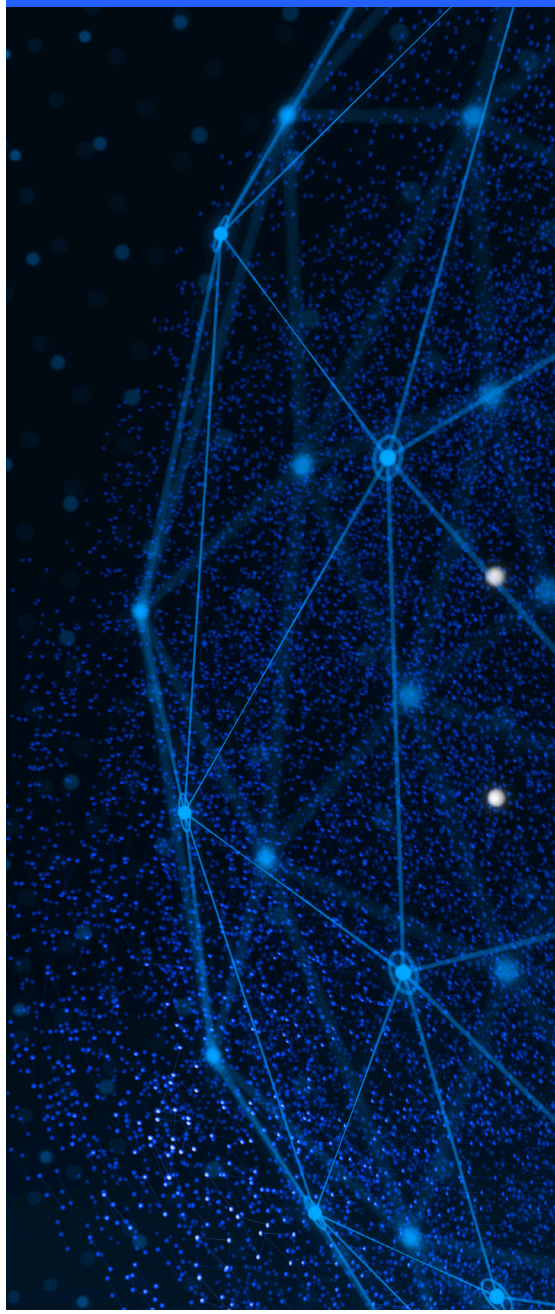
Some pilot projects such as Ponton's "Enerchain" and Blockchain Technology Limited (BTL)'s "Interbit" platforms seek to reduce the costs associated with wholesale energy trading. Software and energy market automation company Ponton has developed **"Enerchain,"** a proof of concept blockchain-based clearing platform for wholesale energy trades that does not rely upon a centralised exchange or brokers.[16] Enerchain allows wholesale energy traders to anonymously send orders to a decentralised "orderbook" that can be accessed by other traders. The trading volumes that occur on the Enerchain platform are still very small compared to total volumes on the European Energy Exchange (EEX). Nonetheless, Enerchain has been expanding. It began in 2017 as a consortium of 15 European energy trading firms. As of April 2018, the consortium had grown to 42 firms.

BTL recently conducted a twelve-week pilot project specifically targeting reconciliation issues in the European gas market.[17] In partnership with Wien Energy, BP, Eni Trading & Shipping and other energy companies, the pilot sought to reduce the manual management of post-trade communications. Rather than sending trade details via email, trades were logged into a blockchain which counterparties could verify in real time. The pilot relied upon BTL's proprietary blockchain platform, **Interbit**, in which it is possible to have one blockchain for every bilateral relation and have all those blockchains connect to one general directory blockchain. In 2018, BTL announced a partnership with Eni Trading & Shipping, Total, Gazprom Marketing & Trading Limited and other companies to use the Interbit blockchain platform to deliver gas trading reconciliation through to settlement and delivery of trades. This enterprise solution is being called OneOffice and is a revenue generating project for BTL.[18]

16 The Enerchain Project, https://enerchain.ponton.de/ (last accessed April 24, 2018).

17 BTL, "BP, Eni Trading & Shipping and Wien Energie Successfully Complete BTL Group's Interbit Energy Pilot, Additional Participants Invited to the Go-to Production Phase," June 5, 2017.

18 BTL, "The BTL™ Interbit™ Blockchain Platform to Drive Next Phase of Energy Trading Systems With Market Leading European Energy Firms," January 21, 2018.



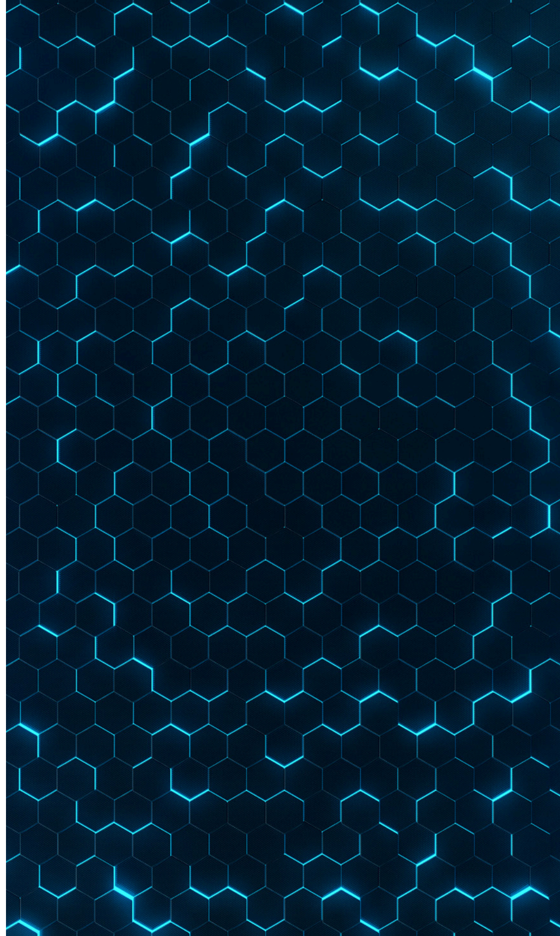
3.1.2 RETAIL ELECTRICITY MARKETS

Similar to in wholesale markets, blockchain could enhance retail electricity markets by using cryptocurrencies for bill settlement and other “meter-to-cash” processes. By enabling the instantaneous settlement of trades, blockchain could reduce the variable costs of payment processing and accounting to that of executing a smart contract. Some envision blockchain-based meter-to-cash automation removing the need for wholesale-to-retail intermediaries altogether. Blockchain could further enrich retail customers by enabling greater transparency into energy charges and bill components, the ability to enter and leave energy contracts more fluidly, and greater choice and transparency into energy supply.

Drift and Grid+ are examples of two startups operating in this space. Seattle-based startup **Drift** is developing a blockchain-based platform that will enable it to act like a competitive energy supplier in deregulated markets.[19] Drift leverages distributed ledger technology, machine learning, and high-frequency trading to directly link independent power generators with residents and small and medium-sized enterprises. Drift delivers bills on a seven-day cycle, with detailed information on fees and sources of energy. Customers have a web dashboard that allows them to track transactions and choose whether they want zero-carbon energy or lowest-cost energy. Customers operate on a contract-free basis.

Austin, Texas-based startup **Grid+** is developing an automated, Ethereum-based platform that will serve as a retailer in deregulated energy markets.[20] By automating billing and settlement, Grid+ aims to provide customers with “nearly frictionless access to the wholesale market.”[21] The project is based on a two-token model and customer-located, Internet-enabled energy gateway called the Grid+ “Smart Agent.” In the short term, this will be primarily used as an automated payment processing unit, reading from the household smart meter and paying for electricity usage in real time (15-minute to 1-hour intervals, depending on the market). It will do so by executing smart contracts onto the Ethereum blockchain using “BOLT” tokens it securely stores in its ewallet (a BOLT is a stable coin representing $1 worth of power from Grid+).

19 Drift, https://www.joindrift.com/ (last accessed April 24, 2018).
20 Grid+, https://gridplus.io/ (last accessed April 24, 2018).
21 Consensys, “Grid+: Welcome to the Future of Energy (White Paper)” no date.



3.1.3 LOCAL PEER-TO-PEER MARKETS

Blockchain technology could enable the development of "peer-to-peer" (P2P) markets in which energy producers and consumers transact on a local scale. By enabling local marketplaces, blockchains could relieve stress on transmission networks (and thereby reduce network costs), improve the economics of small-scale renewables and DER, and enrich customers with greater choice and transparency into energy supply. Much of the focus of blockchain in electricity has been on enabling P2P energy marketplaces. A recent survey found that 57 percent of money raised for blockchain-in-electricity projects is for projects that use blockchain to verify and execute P2P transactions more rapidly.[22]

The general approach to trading electricity using a blockchain—in P2P markets and elsewhere—requires fitting communication hardware or a blockchain network-connected computer to a smart electricity meter. The "blockchain-aware" smart meter acts as point of contact and validation between the electricity system and the blockchain. The meter records electricity generation, imports, and exports. This is converted into tokens, which are allocated to market participants as trades take place, by appending transactions to the blockchain. Coins, which can be held in an "e-wallet" with the meter itself, are normally acquired and redeemed using fiat money or cryptocurrency.

Included in this category is the **"Brooklyn Microgrid Project"**—developed by US-based LO3 Energy—that enables its participants to trade energy using smart contracts via a blockchain.[23] The Brooklyn Microgrid Project uses an Ethereum-based, energy market-specific platform to enable producers and consumers to trade locally-generated electricity. Smart contracts are employed to tokenize green certificates—representing the net surplus energy generated by producers, as recorded by blockchain-aware meters—and to create the P2P market where these certificates are exchanged. The project's first transaction—connecting five homes with solar photovoltaic (PV) production to five customers—was successfully executed in early 2016. By the end of 2017 the Project had scaled to include about 60 solar sites and 500 consumers.[24]

In Austria, the companies **Verbund** and **Salzburg AG** have developed a blockchain P2P proof of concept that enables tenants to exchange shares of the generated electricity from their roof via a distributed blockchain app on an android tablet.[25] These shares are stored on a proof-of-work blockchain, which is operated by the tenant themselves. The grid operator Salzburg Netz GmbH then collects the transaction data via a read-only access and allocates the own consumption to the individual household bills.

22 Metelitsa, C., March 2018.

23 Brooklyn Microgrid Project, https://www.brooklyn.energy/ (last accessed April 24, 2018).

24 Fehrenbacher, K., "Siemens Invests in LO3 Energy, Making Blockchain a Piece of Its Microgrid Strategy," Greentech Media, December 26, 2017.

25 Futurezone, "Verbund und Salzburg AG starten Blockchain-Pilotprojekte," November 13, 2017.

BLOCKCHAIN COULD HELP PROVIDE SUCH FLEXIBILITY SERVICES BY RECORDING RESOURCE AVAILABILITY AND AUTOMATING DEMAND RESPONSE AND DER ACTIVITY IN REAL TIME.

This translates to optimised own consumption within buildings (e.g. customers can shift flexible loads like electric car charging) and savings due to lower grid fees. The main innovation tested in this proof of concept is the transfer of the data sovereignty over the generation shares from the grid operator to the customers in the context of the "Mieterstrom"-reform (tenant supply) and the new user experience with a blockchain-enabled app.

Another example of this type is "Jouliette," a blockchain-supported showcase microgrid collaboration between Amsterdam's De Ceuvel sustainable office park, Dutch DSO Alliander, and energy solutions developer Spectral.[26] The site comprises 16 ships/buildings, rooftop PV panels, various types of businesses and appliances, and a single shared grid connection. Launched in September 2017, the microgrid uses the Jouliette token to reward, manage and share locally produced energy. It also uses Alliander's "Icarus" algorithm to forecast location-specific solar generation.

26 Jouliette at De Ceuvel, https://jouliette.net/ (last accessed April 25, 2018).

3.1.4 FLEXIBILITY SERVICES

In many power markets, variable wind and solar generation is challenging system operators' abilities to balance short term supply and demand without curtailing renewable generation. The potential benefit of achieving greater power system flexibility is large. For example in 2016, customers in Germany served by the TSO paid approximately €800 million for measures (redispatch, grid reserve, wind power curtailment) to ensure that electricity transport was within the limits and capabilities of the grid.[27] Demand for new "flexibility" services, that adjust demand or inject power to contribute to short term balancing, has increased in recent years. Blockchain could help provide such flexibility services by recording resource availability and automating demand response and DER activity in real time. Pilot projects and startups operating in this space include pilot projects led by grid operator TenneT, and UK-based Electron's "Flexibility Marketplace."

27 TenneT, "Europe's first blockchain project to stabilize the power grid launches: TenneT and sonnen expect results in 2018," November 2, 2017.

TenneT, a transmission system operator, has partnered with Vandebron, Sonnen, and IBM on blockchain-based projects that are intended to enhance flexibility services available to the operator.[28] In TenneT's pilot project with Vandebron, Vandebron will work with electric vehicle (EV) owners to make EV battery capacity available to help TenneT balance the grid. Vandebron will provide this service without compromising the availability of EV owners' car batteries. Blockchain technologies have enabled EVs to participate by recording their availability and their actions in response to signals from TenneT.

28 Electron, http://www.electron.org.uk/#our_products (last accessed April 25, 2018).

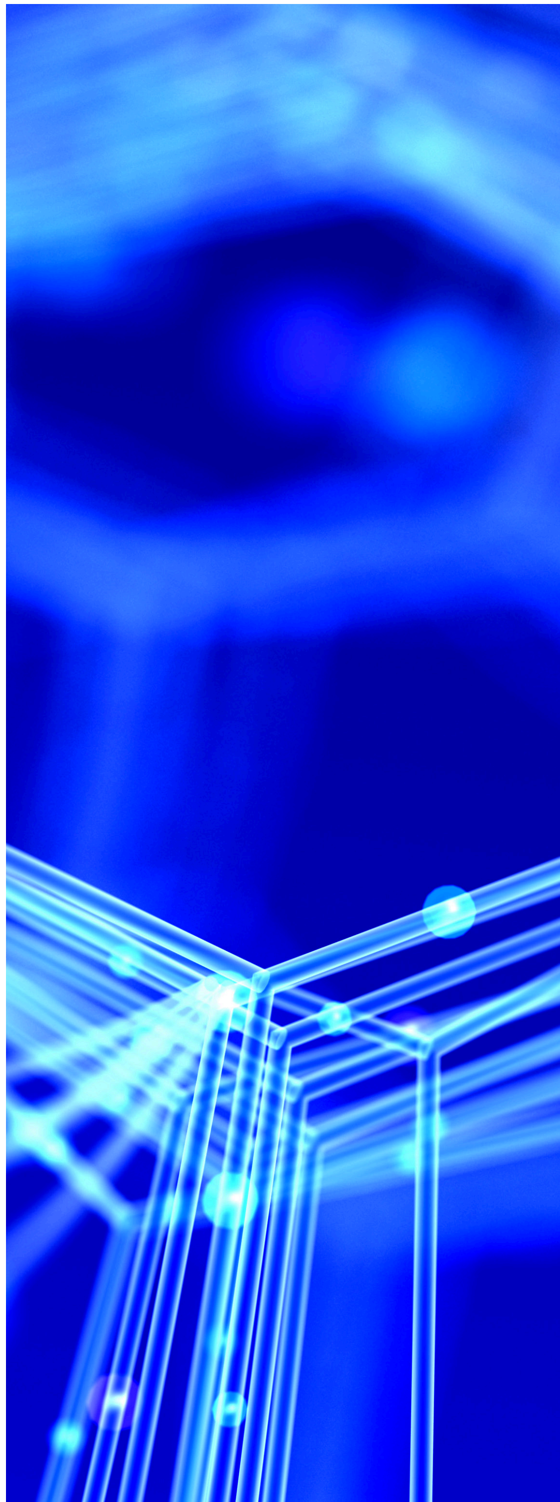
In TenneT's pilot project with sonnen eServices, a group of residential batteries has been made available to help balance wind energy intermittency during periods of network congestion, when other generators may not be able to contribute to balancing. A blockchain-based interface will enable TenneT to view the status of flexible resources, to dispatch resources, and to maintain a record of the batteries' contributions to grid balancing.

London-based **Electron** is also using blockchain technology for flexibility trading.[29] With market design and technical support from National Grid and Siemens, respectively, the startup developed a decentralized demand response platform that was awarded a grant from the U.K. government's Energy Entrepreneurs Fund in September 2017. The company has now founded a consortium aimed at co-developing a commercialization model for the platform. The consortium partners include Baringa, EDF Energy, Flexitricity, Kiwi Power, Northern Powergrid, Open Energi, Shell, Statkraft, and UK Power Networks.

3.1.5 ELECTRIC VEHICLE CHARGING AND COORDINATION

As electric vehicles (EVs) become more prominent, system operators are faced with the challenges of supplying new EV-related mobile load and, potentially, using surplus stored energy to improve system flexibility. Blockchain technology could improve EV charging coordination by facilitating energy payments at charging stations, and by enabling drivers to make charging decisions based on map and real-time pricing data.

An example of an active project in this space is MotionWerk's **"Share&Charge"** app. In 2016, Innogy (a subsidiary of German utility RWE) partnered with German blockchain startup Slock.it to create a P2P service allowing EV and charging point owners to rent their charging infrastructure to each other autonomously without the need for an intermediary. By May 2017, Innogy's "Innovation Hub" incubator had spun out a startup, MotionWerk. It's first product, "Share&Charge," allowed EV owners to charge their vehicles by making digital payments using



29 Add citation

a mobile app.[30] Charging point owners used the application to make their infrastructure available, set tariff structures and to collect fees. Until April 2018, the service was available to about 1,000 EV owners with 1,250 private and public charging points registered in Germany. The system used an e-wallet and smart contracts on the public Ethereum blockchain as P2P transaction layer, including a Euro-backed "Mobility Token." Share&Charge was the world's first e-mobility transaction platform that used blockchain. Based on end-customer experience and learnings from different pilot initiatives in the EU and the US that MotionWerk conducted (e.g. the Oslo2Rome project), Share&Charge is currently transforming into an open source and decentralised digital protocol for electric vehicle charging. It is envisaged to allow charge point operators and e-mobility service providers to fully decentralise their e-mobility assets to, next to other benefits, simplify processes of controlling, payment and settlement of charging EVs.

Share&Charge is also being tested outside Germany. US-based EV charger company eMotorWerks (an Enel group company) has been testing a blockchain-based peer-to-peer charging marketplace in California, allowing drivers to pay each other for use of their home chargers.[31] eMotorWerks is using the Share&Charge platform.

3.1.6 NETWORK MANAGEMENT AND SECURITY

The distribution system is becoming more complex due to the inclusion of DER and digital technologies. Modern DSOs and TSOs are faced with the challenges of better understanding the present state of the system and storing and analysing very large quantities of data. Simultaneously, increased digitisation has increased power system vulnerability to cyberattacks.

Blockchains could enhance network management by automatically maintaining verifiable network asset condition data. Moreover, blockchain technology could naturally protect against grid-related cyber-threats due to its inherent redundancy and the fact that it is tamper-proof and does not have a single point of attack.[32]

There are few active projects that are using blockchain technology to enhance network management and security. One is being spearheaded by the cybersecurity company Guardtime. Guardtime is using permissioned blockchain-based systems to protect the UK's nuclear power stations, electricity grid, and other critical infrastructure.[33] Guardtime's solution, called Keyless Signature Infrastructure (KSI), allows for the verification of time, location, and authenticity of signed data, and allows for continuous monitoring of systems operation, enhanced veracity of historical data, and improved cybersecurity for critical infrastructure.

30 Share & Charge, http://shareandcharge.com/en/ (last accessed April 25, 2018).

31 eMotorWerks, https://emotorwerks.com/ (last accessed April 25, 2018).

32 Morris, J., "How the blockchain could fight grid cyber-threats," GreenBiz, May 31, 2017.

33 Guardtime, "KSI Technology Stack," https://guardtime.com/technology (last accessed April 25, 2018).

3.1.7 ENVIRONMENTAL ATTRIBUTE MARKETS

Market-based systems to promote renewable energy deployment and greenhouse gas emissions reductions exist in many countries and jurisdictions. These include carbon offset mechanisms, carbon taxes, and cap and trade systems. Common challenges with such systems include the costly reliance on manual audit practices, limited geographic scale, and centralised and opaque management. Such challenges can result in high transaction costs and even fraud. Some of these challenges can be addressed by "tokenising" renewable attributes and storing them on a blockchain. Storing environmental attribute creation and transactions on blockchains could eliminate the need for a central verification agency, because given appropriate governance systems, data stored on a blockchain can be rendered accurate and secure.

An example of a project in this space is SolarCoin, a solar-incentivising cryptocurrency whose goals are to reduce audit costs, improve transparency, and improve liquidity for solar-derived credits.[34] SolarCoin is sent to solar generators after claims of generation by registered facilities are sent to the SolarCoin Foundation or an affiliate organisation. Claims may also be generated automatically by smart meters, and all such transactions are visible on the SolarCoin blockchain. As of March 2018, SolarCoins have been granted in 58 countries and growing demand for the cryptocurrency is ultimately meant to incentivise renewable generation.

Design company innovation laboratory, IDEO CoLab, has integrated its capabilities with Nasdaq's Linq platform as well as IoT company Filament's hardware—which uses digital sensors with blockchain capabilities—to issue renewable energy credits (RECs) to producers for each kilowatt-hour their solar panels generate.[35] The pilot project seeks to enable small solar producers to easily track, prove, and trade power.

STORING ENVIRONMENTAL ATTRIBUTE CREATION AND TRANSACTIONS ON BLOCKCHAINS COULD ELIMINATE THE NEED FOR A CENTRAL VERIFICATION AGENCY, BECAUSE GIVEN APPROPRIATE GOVERNANCE SYSTEMS, DATA STORED ON A BLOCKCHAIN CAN BE RENDERED ACCURATE AND SECURE.

34 SolarCoin, https://solarcoin.org/en/node/6 (last accessed April 25, 2018).
35 Ideo CoLab, "Smart Solar," https://www.ideocolab.com/prototypes/smartsolar (last accessed April 25, 2018).

3.2 The limitations and risks of blockchain

Despite the abundance of blockchain-based projects and their potential applications, the future of blockchain in electricity is uncertain. Several limitations, risks, threats, and challenges contribute to this uncertainty. Popular blockchain implementations remain burdened by high costs, slow transaction speeds, and other technological limitations and risks. Characteristics of the electric power sector—such as the presence of economies of scale and scope in distribution system operation—may challenge the ability of certain blockchain-based applications to grow. Moreover, blockchains face competitive pressures and public perception challenges.

3.2.1 TECHNOLOGICAL LIMITATIONS AND RISKS

The high costs and slow speeds characteristic of public and permissionless PoW-based blockchains, the most popular and proven type, limit their deployment in the electric power sector. As described in Section 2, high costs and slow speeds stem from energy-intensive consensus mechanisms and the maintenance of large distributed ledgers. While faster blockchain systems like the PoA-based Tobalaba Energy Web Foundation test network promise greater scalability, such scalability requires foregoing some of the desirable properties associated with PoW-based blockchains. Blockchains are encumbered by a "scalability trilemma"in that they only have at most two of the following three properties: decentralisation, scalability, and security.[36] Until further innovation is brought to bear, blockchains are not appropriate for large scale deployment in power systems.

A separate risk is that a blockchain's security remains unproven until it has grown enough to be attractive to cyber-attackers. Code repositories are written by humans and bugs often persist despite quality assurance measures. Blockchains with bugs can last without evidence of attack if they are not valuable enough to entice attacks, and when attacks do occur the consequences can be large. For instance, in 2016, an unknown attacker was able to exploit faulty code in an Ethereum-based application called "The DAO," and channel funds of around $50 million to a private account.[37] The oldest and most time-tested networks such as Bitcoin are often considered the safest.

THE HIGH COSTS AND SLOW SPEEDS CHARACTERISTIC OF PUBLIC AND PERMISSIONLESS POW-BASED BLOCKCHAINS, THE MOST POPULAR AND PROVEN TYPE, LIMIT THEIR DEPLOYMENT IN THE ELECTRIC POWER SECTOR.

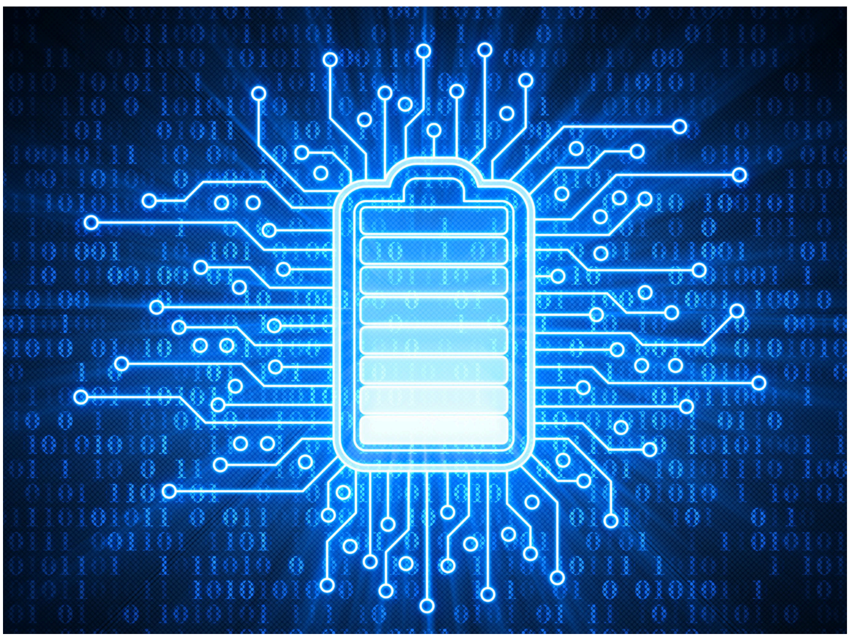
36 GitHub, "Sharding FAQ," https://github.com/ethereum/wiki/wiki/Sharding-FAQ (last accessed April 25, 2018).
37 Price, R., "Digital currency Ethereum is cratering because of a $50 million hack," Business Insider, June 17, 2016.

A related challenge is that it is often unclear who bears legal and technical responsibility for a blockchain when there are security breaches or other unforeseen events (such as an electricity price spike). Public blockchains are inherently decentralised and users are anonymous (or pseudonymous). Without a central authority or insurer, users are fully exposed to the risk of cyberattacks and other unforeseen events.

Another risk concerns the lack of flexibility of blockchains once they are deployed. Once live, blockchains require significant stakeholder buy-in before large upgrades can be made. Without such buy-in, there is a risk of disagreeing sub-communities "forking" their blockchains and becoming adversarial. When considering blockchains related to physical assets like power systems infrastructure, the threat of forking becomes much more dangerous. For instance, two different stakeholders cannot simultaneously own the same right to the same solar panel. Balancing tradeoffs between decentralisation and flexibility may prove to be a critical challenge for the development of blockchain.

Lastly, there are unresolved user-friendliness challenges. Most blockchain platforms feature asymmetric cryptography, in which public and private keys are used to manage identities and sign transactions. Users are required to safeguard their private key to participate in blockchains. If they lose their keys they also likely also lose their digital assets. An additional user-friendliness challenge has to do with the protection of user privacy. Maintaining user privacy requires that all data pertaining to that user is encrypted. Reliable, secure, and private accessibility can be challenging on a blockchain and is an active area of blockchain research.

ONCE LIVE, BLOCKCHAINS REQUIRE SIGNIFICANT STAKEHOLDER BUY-IN BEFORE LARGE UPGRADES CAN BE MADE. WITHOUT SUCH BUY-IN, THERE IS A RISK OF DISAGREEING SUB-COMMUNITIES "FORKING" THEIR BLOCKCHAINS AND BECOMING ADVERSARIAL.

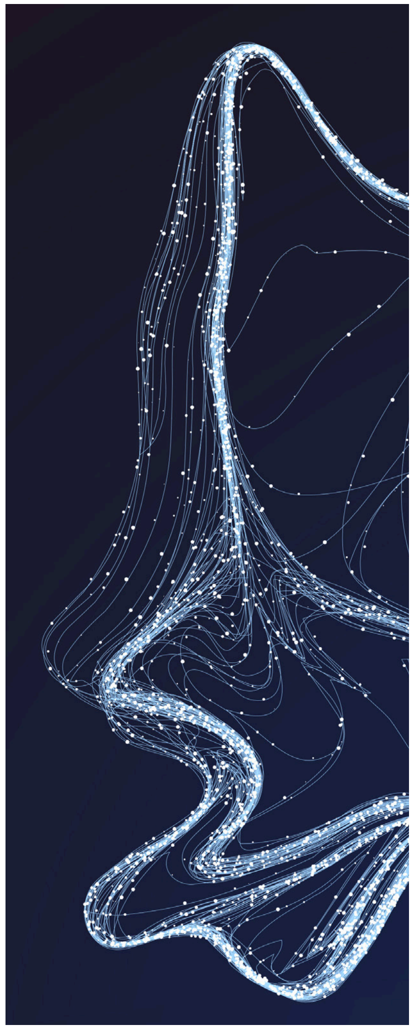


3.2.2 POTENTIAL LIMITATIONS ASSOCIATED WITH THE STRUCTURE OF THE ELECTRICITY INDUSTRY

The operation of electricity networks is widely considered a "natural monopoly" activity. Put simply, this means that the transmission and distribution of electricity services are provided at least cost by a single entity— either a TSO or DSO—rather than by competing firms. "Economies of scale" are said to exist in the operation of the transmission and distribution networks: the average cost of network operation for a grid operator declines as the size of the operated network increases.

In their roles as natural monopolies, network operators are uniquely responsible for certain functions. TSOs, for example, are solely responsible for maintaining a grid-wide balance between electricity supply and demand at all times. All electricity trading—including local P2P trading—must be reconciled with the TSO, who bears the responsibility of maintaining the security of the grid. Thus, while robust P2P communities may emerge, they are unlikely to ever function independently from grid operators, so long as they remain connected to the central grid.

In addition to economies of scale, "economies of scope" are thought to exist in services related to network operation. Because of their familiarity with their network's operational characteristics and planning requirements, network operators are likely to provide a range of related services at lower cost than if those services were competitively provided. For example, DSOs may be able to effectively coordinate the dispatch of DER-provided bulk power system services at lower cost than independent organisations that are less familiar with the network, or than disintermediated blockchain-based platforms. Thus, to the degree that DER-to-wholesale markets emerge, there may be significant advantages to having DSOs coordinate these markets, rather than having these markets function largely on a disintermediated basis.

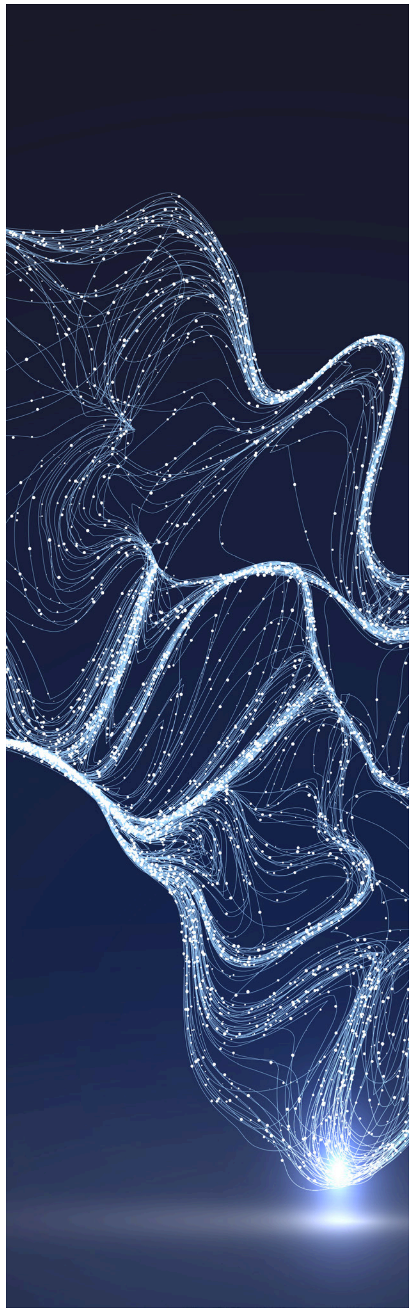


THE HIGH COSTS AND SLOW SPEEDS CHARACTERISTIC OF PUBLIC AND PERMISSIONLESS POW-BASED BLOCKCHAINS, THE MOST POPULAR AND PROVEN TYPE, LIMIT THEIR DEPLOYMENT IN THE ELECTRIC POWER SECTOR.

3.2.3 COMPETITIVE PRESSURES AND PUBLIC PERCEPTION CHALLENGES

Alternative technological solutions exist for many of the potential applications being explored by blockchain projects. For example, with respect to enabling customer and DER participation in wholesale markets, telemetry-based communication systems have emerged as a potential solution.[38] It is not clear that proposed blockchain-based solutions for enhanced customer and DER market participation would outperform telemetry-based and other technologies. Moreover, there are many ways to protect against power system cyberattacks.[39] DSOs and TSOs have well-established practices for managing and securing their networks. It is not clear that proposed blockchain-based solutions offer an improvement upon alternatives in many regards.

Finally, along with competitive pressures, blockchain technologies face public perception challenges. Blockchain technologies are commonly associated with the "shadow economy" and have only recently started to gain public legitimacy. Furthermore, blockchain has "hype" characteristics that are typical of promising emerging technologies. In a recent report by the research and advisory firm Gartner, blockchain technologies are described as moving past a "Peak of Inflated Expectations" into a "Trough of Disillusionment", in which interest for the technology will wane as experiments and implementations fail to deliver.[40] As evidenced by recent cryptocurrency price crashes, even blockchain's most mature application struggles to retain the trust and confidence of its users.



38 For example, see Taft, J.D., "DER Telemetry Communication Architecture for ESOs, DSOs, and System Operators," Pacific Northwest National Laboratory, November 2017.
39 For example, see Wang, W. and and Z. Lu, «Cyber security in the smart grid: Survey and challenges,» Computer Networks 57:1344-1371 (2013).
40 Panetta, K., «Top Trends in the Gartner Hype Cycle for Emerging Technologies, 2017,» Gartner, August 15, 2017.

4. Conclusion

Blockchain offers a solution to guarantee the validity of a transaction by recording it not only on a main register but a connected distributed system of registers, all of which are connected through a secure validation mechanism. It offers a way for untrusted parties to reach agreement on a common digital history that might otherwise be easily faked or duplicated, all without using a trusted intermediary. Because of this, some industry experts predict blockchain technologies will accelerate a transition to a more distributed energy industry, in which more accurate and rapid transactions can occur.[41] As reported in Section 3.1, many companies and consortia in the electricity sector are actively investing in blockchain projects. Potential applications span the entire electricity sector from local, retail, and wholesale electricity markets to network support services, electric vehicle integration, and environmental attribute markets.

Nonetheless, blockchain technology's future in electricity systems is uncertain. Blockchain represents new technologies with no scaled commercial applications in the electricity industry. The technology class is currently burdened by high costs, slow transaction speeds, and other limitations and risks. Unique characteristics of the electric power sector—such as the presence of economies of scale and scope in network operation—challenge the ability of certain blockchain-based applications to grow. Moreover, blockchains face competitive pressures and public perception challenges. Much more experimentation and innovation are required before the potential value of blockchain to the electricity sector becomes clear.

41 Basden, J. and M. Cottrell, «How Utilities Are Using Blockchain to Modernize the Grid,» Harvard Business Review, March 23, 2017 (updated March 27, 2017).