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DISCUSSION PAPER

Applying Blockchain Technology to Electric Power Systems

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Introduction

Electric power systems around the world are rapidly changing. For over a century, these systems have relied largely on centralized, fossil fuel plants to generate electricity and sprawling grids to deliver it to end users. Utilities had a straightforward objective: provide electricity with high reliability and at low costs. But now, governments have new ambitions for electric power systems. Many are requiring these systems to rely heavily on volatile wind and solar power; several are also aiming for a high share of electric vehicles (EVs), which can strain grids. Further complicating the matter, customers are installing their own equipment—from solar panels to batteries and smart appliances—to control their production and consumption of electricity.

As utilities struggle to sustain reliable service, meet new policy objectives, and cope with rising complexity, innovators are peddling a putative solution: blockchain technology. A blockchain is a way to record and verify transactions without requiring a central entity to maintain or validate the ledger. Its most popular application is in recording peer-to-peer transactions of bitcoin and other so-called cryptocurrencies. When users trade bitcoin, a vast, distributed network of computers verifies and records the transaction, which is immutably stored in the bitcoin blockchain and is visible to all users. In theory, blockchain technology could enable swift, frictionless, secure, and transparent currency trading. In 2017, the price of bitcoin shot up more than twenty-fold, and other cryptocurrencies enjoyed a similar increase.

But the potential applications of blockchain extend well beyond currency trading; blockchain could also be used to cope with increasingly complex electric power systems. In 2017, start-up companies raised over $300 million to apply blockchain technology to the energy sector in myriad ways.[1] Some of these start-ups want to enhance existing markets for trading electricity or even to create new ones, for example, by using blockchain to facilitate peer-to-peer transactions that bypass a central utility or retail energy provider. Others hope to use blockchain to track the production of clean energy. Still others have proposed using blockchain to make it easier to pay for charging EVs, raise funds to deploy clean energy, manage customer appliances, and more.

Proponents of blockchain technology liken its potential to that of the internet three decades ago. But so far, little of this potential has been realized. This paper assembles the largest publicly available dataset of initiatives applying blockchain to the electric power sector. It includes dozens of interviews with startups, nonprofits, and established firms, as well as case studies of leading startups with pilot projects across multiple continents.[2] Although most blockchain ventures aim to replace today's centralized power system with decentralized energy trading, the ventures most likely to achieve commercial traction in the coming years will largely work within the existing system and partner with incumbents such as utilities.

Because the electric power sector is highly regulated, policymakers will play a crucial role in determining how much of blockchain's potential can be realized. In order to effectively regulate blockchain, policymakers should first invest in understanding it. Next, they should actively support the development of technical standards. And finally, policymakers should make it possible for blockchain ventures to set up small-scale demonstration projects, for example, by creating regulatory sandboxes that loosen electric power sector regulations to permit experimentation.

Background and Context

Over the last decade, the electric power sector has begun to change profoundly. And over that same time, blockchain technology has emerged as a powerful tool to manage complexity in a digital world. The confluence of the two trends explains the surging investment in new ventures that apply blockchain to energy.

THE CHANGING ELECTRIC POWER SECTOR

For over a century, electric power systems around the world have shared several characteristics. First, they have relied largely on centralized power plants, most of which run on fossil fuels such as coal and natural gas. Second, centralized system operators, such as utilities or regional transmission authorities, have managed sprawling electricity grids and scheduled the production and delivery of electricity, which has flowed in one direction, from centralized generators to decentralized end users. In this arrangement, consumers have had minimal control over their electricity use, and system operators have relied on flexible power generators to meet the needs of inflexible and unpredictable consumers. Third, system operators have had minimal real-time information about the operation of the power grid, especially the equipment on the distribution grid closest to end users and the real-time usage of customer devices (typically, customers have had to inform utilities that a blackout has occurred).[3]

All three of these realities still characterize most electric power systems around the world, but each of them has begun to change over the last decade. First, the undisputed reign of centralized, fossil fuel plants is under threat from the rise of distributed power generation—which includes rooftop solar panels, fuel cells, batteries, microturbines, and other locally sited power sources—and cheap renewable energy. Thanks to government support for, and the plunging costs of, renewable energy, wind and solar power are projected to supply over 10 percent of global electricity supply within the next five years, chipping away at the dominance of fossil fuels.[4] The majority of renewable energy capacity has been deployed at large scales, but solar power in particular can be deployed at much smaller scales in decentralized applications, for example, on rooftops of residential and commercial buildings. Customers are also installing a wider range of equipment to manage their power consumption, such as programmable thermostats and building energy management systems; such equipment, as well as distributed power generators, collectively are called distributed energy resources.

The rise of renewable and distributed energy is complicating the second characteristic of conventional power systems: centralized grid management. Whereas previously system operators could control the power supply from flexible power plants to meet fluctuating customer demand, now a rising share of electricity supply comes from wind and solar generators, which have outputs that fluctuate with the weather. In addition, the proliferation of distributed energy sources makes operating centralized systems more complex. Finally, customers are increasingly empowered to control their own energy consumption and production, by installing either distributed energy sources such as solar power or smart devices capable of managing electricity consumption. For example, commercial building owners are able to marshal on-site batteries and energy management software to alter their demand and save on electricity bills; residential customers can control everything from their EV charging to their smart thermostat settings to manage their power use. Ultimately, these capabilities could help the grid balance supply and demand. But for now, the complexity added by empowered customers is mostly taxing the conventional model of centralized grid management.[5]

The third change is the digitalization of the electric power sector, which is creating vast amounts of operational data that has yet to be harnessed. In 2016, firms worldwide invested over $47 billion in digital upgrades to electric power systems, adding sensors to the transmission and distribution grids, modernizing outdated information and communications technology (ICT) platforms, and more.[6] And over the last decade in the United States, utilities have provided smart electricity meters to over half of all customers; these smart meters collect data on customer energy use every hour or even more frequently.[7] As a result of this ongoing investment in digitalization, system operators are slowly gaining the capability to monitor the real-time operation of the grid, from local imbalances in supply and demand across the distribution network to the consumption profiles of customers.

So far, these changes are still incipient; electric power systems today work largely as they did in the twentieth century. But these changes will become more pronounced over time, and they have already caused problems around the world. In Australia, spiking power prices and rolling blackouts have accompanied the rise of intermittent renewable energy.[8] And in California, where residents are enthusiastic early adopters of distributed solar power and EVs, utilities might need to make costly upgrades to distribution grids to handle excess supply and demand in some neighborhoods.[9]

A major problem is that power utilities are risk-averse entities that are slow to adapt to the changing electric power landscape, in part because they face scrutiny from regulators as well as pressure from shareholders seeking stable returns. Yet only decisive action by utilities can direct the transformation of electric power systems and deliver reliable energy more cheaply, cleanly, and efficiently. Sophisticated prosumers (consumers of electricity who also produce it) could deploy their smart energy equipment to help the grid match demand with volatile renewable energy supply. Rather than straining the grid, EVs—as fleets of mobile batteries—could back up the grid. And utilities, customers, and third-party firms could collaborate to harness the vast streams of real-time operational data to ensure the smooth functioning of the power system.

Blockchain technology could make all of this possible, argues a growing cohort of start-ups. That claim is almost certainly an exaggeration. Nevertheless, some compelling applications of blockchain, in concert with a suite of other technologies, could, in the coming decades, underpin several core aspects of managing the electric power system.

BLOCKCHAIN BASICS

In 2008, Satoshi Nakamoto—a pseudonym for a person or a group whose identity remains unknown—released a white paper describing a system for peer-to-peer trading of a digital currency known as bitcoin. All bitcoin transactions would be recorded in a blockchain—a digital, decentralized, and publicly available ledger. Network participants would be able to transact over the internet without a central authority processing and validating those transactions. In theory, transactions on a decentralized blockchain network could be processed and verified with fewer intermediaries, lower transaction fees, and greater security than those conducted on traditional centralized platforms.[10]

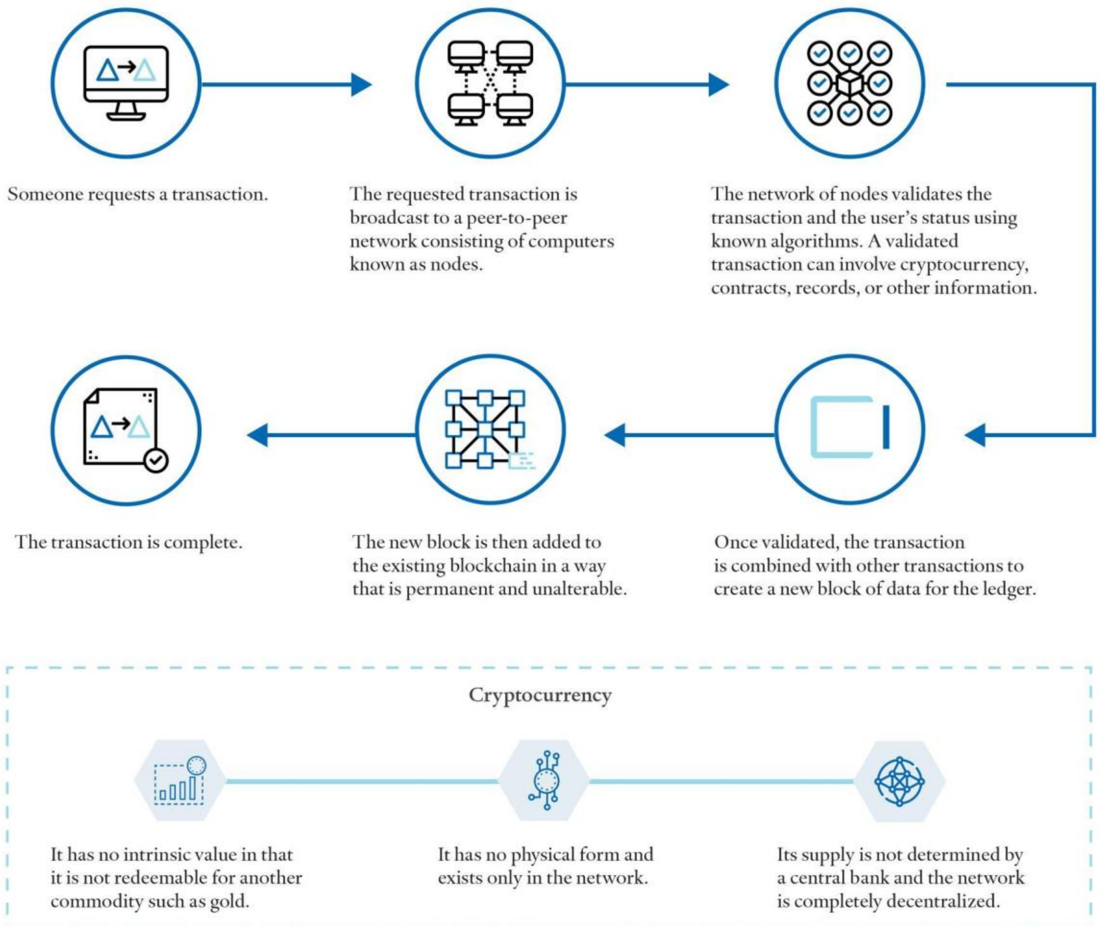
In the case of the blockchain network that underpins bitcoin, each computer connected to the network stores a copy of the blockchain, which is a running history of all bitcoin transactions. When a user initiates a bitcoin payment, other computers connected to the network validate the transaction, coming to a consensus that the transaction is in fact valid and not a case of double-spending (the same digital token being spent more than once). Approximately every ten minutes, a list of new transactions is bundled together into a "block" for all network participants to add to their local copies of the blockchain ledger of transactions. Because of the way the blockchain is cryptographically constructed, it is virtually impossible to alter the transaction history recorded in the digital ledger.[11]

Computers connected to the network around the world help verify new transactions because they are rewarded with newly issued bitcoin for successfully doing so. Known as miners, these computers compete with one another to solve computationally intensive math problems (these problems amount to busywork, but as a consequence of solving them, miners happen to verify each new block of transactions added to the blockchain ledger). Once a computer wins, the competition begins anew to verify the next block. This arrangement has incentivized hundreds of thousands of bitcoin miners to compete for bitcoin payments and, in the process, facilitated the decentralized verification of millions of bitcoin transactions every year. (Mining—and bitcoin, by extension—has been criticized for the huge amount of energy consumed by powerful computers; by some estimates, bitcoin mining uses more electricity than all of Ireland. [12] More energy-efficient methods of validating transactions are under development.[13]) Although the use of bitcoin for financial transactions is still dwarfed by the use of conventional currencies, financial markets are ascribing significant, albeit volatile, value to bitcoin.[14] After a year of appreciation, the global value of bitcoin topped $300 billion toward the close of 2017 before collapsing to around $100 billion in mid-2018.[15]

Other cryptocurrencies have emerged alongside bitcoin, all of which also use a blockchain ledger to record transactions but differ in their exact implementations. The Ethereum platform—with tokens of value (known as ether) that command a market capitalization second to that of bitcoin—could enable a much broader range of blockchain applications because of its ability to encode so-called smart contracts. In an Ethereum transaction, users can write code onto the blockchain ledger that stipulates the conditions under which payment will automatically be remitted. For example, a shipping firm might set up a smart contract under which the customer will pay the firm in ether tokens only after a package has been delivered. A data stream from a GPS tracker on the package might then trigger the smart contract to execute payment once the package reaches its destination. In this way, smart contracts running on a blockchain can eliminate the need for a central authority to enforce a contract.[16]

Although blockchains such as Bitcoin and Ethereum are helpful to illustrate the technology's capabilities, a cryptocurrency is not actually a necessary component of a blockchain network. A blockchain can be used as a ledger to store a variety of transactions, from currency payments to contract execution and asset registration (see figure 1). Moreover, not all blockchains are public, as Bitcoin and Ethereum are. In the case of Bitcoin, any computer connected to the internet and running the Bitcoin client software can participate in verifying transactions to be appended to the ledger, which is then publicly visible. Private and consortium blockchain networks, such as IBM's Hyperledger and JPMorgan's Quorum, only allow those entities that have the permissions to view and validate transactions on the ledger.[17] These alternatives to public blockchain networks can process transactions faster and enable the entities that manage these networks to keep sensitive user data confidential and better protect their networks against cyberattacks. However, centralized oversight undercuts the nonhierarchical, decentralized architecture of the earliest blockchains; therefore, some critics argue, private blockchain networks should instead be labeled distributed ledgers.

Figure 1. How a Blockchain Network Records Transactions on a Digital Ledger



Source: Recreated with permission from Blockgeeks.

Disagreements over the benefits of different blockchain platforms and cryptocurrencies and the trade-offs among public and private blockchains signal that blockchain technology is evolving. Its first decade has had mishaps: prominent cyberattacks on cryptocurrency exchanges have erased millions of dollars' worth of digital currency, and the market values of bitcoin and other cryptocurrencies have gyrated wildly.[18] Moreover, speculative investment in new and unproven blockchain ventures is growing. Many start-ups are bypassing conventional methods of fundraising from established venture capital investors and instead crowd-funding investment through so-called initial coin offerings (ICOs), in which a blockchain venture sells cryptocurrency tokens that will have utility within its network ecosystem. Start-ups raised over $5 billion through ICOs in 2017, but market analysts warn that many of these ICOs are scams, and the U.S. Securities and Exchange Commission has launched investigations to crack down on fraudulent offerings.[19]

This flurry of activity is a result of the transformative potential blockchain has. Some observers liken blockchain to the Transmission Control Protocol/Internet Protocol (TCP/IP) suite that enabled the internet. By this analogy, applications such as cryptocurrency trading facilitated by the blockchain are similar to email and e-commerce facilitated by the internet. In the future envisioned by blockchain proponents, a rich application layer built atop a blockchain architecture can revolutionize disparate fields, from health care to financial services and energy. In each of these fields, however, blockchain will have to surmount obstacles to upend the existing order. Initiatives to apply blockchain to reimagine the electric power sector, in particular, will encounter economic and regulatory structures that are resistant to rapid change.

Blockchain and the Electric Power Sector: Actors and Applications

Blockchain technology can be a tool for managing increasingly complex electric power systems, even as more intermittent renewable energy flows into the grid and customers connect new equipment to produce, store, and consume energy. Recognizing this, diverse entities have recently launched ventures to harness blockchain in a myriad ways, including both for-profit and nonprofit undertakings (see appendix for the full list). Roughly half of them use a public blockchain; the other half use private or consortium blockchains.

Start-up companies account for the majority of new blockchain ventures. From March 2017 to March 2018, start-ups raised over $300 million to apply blockchain to the energy sector. Almost 75 percent of the funds they raised came through ICOs, compared to just 20 percent from traditional venture capital sources.[20] Still, start-ups face serious barriers to commercializing their technologies.

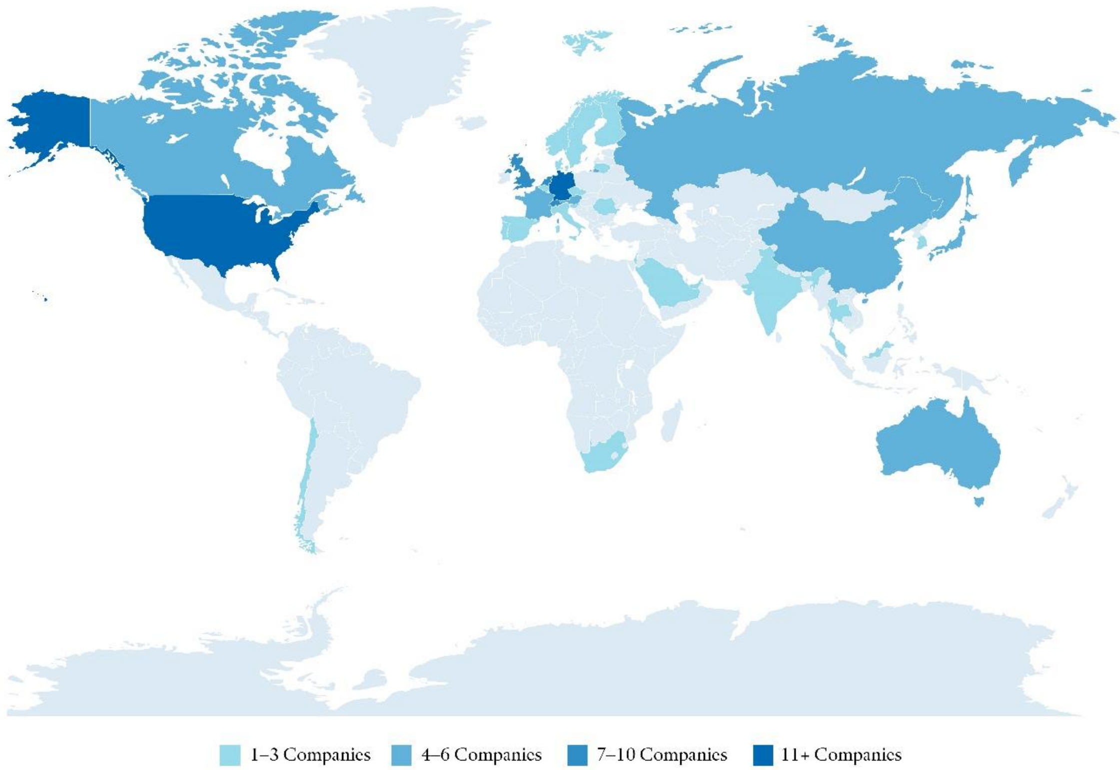
Around the world, electric power systems are heavily regulated, and utilities often have a monopoly over operating the grid and delivering electricity to end users. Fortunately for blockchain's prospects, utility-sponsored initiatives comprise the second most numerous category of blockchain ventures. From the Tokyo Electric Power Company (TEPCO) in Japan to E.ON in Germany, established firms in the electric power sector are launching their own initiatives or partnering with start-ups.[21] Some of these firms own power plants and trade the electricity they produce in wholesale electricity markets; those firms see blockchain as a way to improve the functioning of the markets. Others operate transmission and distribution grids and hope that blockchain can help them do so more efficiently in the face of rising system complexity. By virtue of these firms' dominant positions in the electric power sector, utility-sponsored blockchain initiatives have a greater chance of achieving commercial traction.[22]

Another category of actors comprises other corporations—both in the broader energy sector and in other industries—as well as nonprofits. For example, major European oil companies such as Shell and Statoil have partnered with the nonprofit Rocky Mountain Institute to support the Energy Web Foundation, which aims to develop a standard blockchain platform upon which energy applications can be built. Other initiatives, such as Hyperledger and the Enterprise Ethereum Initiative, bring together corporations such as Toyota and Intel to develop blockchain standards across various industries, including energy.[23]

Yet another category includes the public sector. A smattering of governments and public sector organizations—including the government of Dubai; U.S. national laboratories; and energy regulators in Singapore, the United Kingdom, and Australia—have signed on to initiatives to develop standards and test blockchain applications such as energy trading. Involvement of public sector entities such as regulators will be crucial to blockchain's commercial prospects because the electric power sector is so highly regulated.[24]

These various actors are sponsoring energy and blockchain initiatives on every continent save Antarctica—most of them are in Europe, followed by North America (see figure 2). This geographic spread means that blockchain ventures will confront a wide range of regulatory regimes and electric power system characteristics, and they will have abundant opportunities to learn across regions.

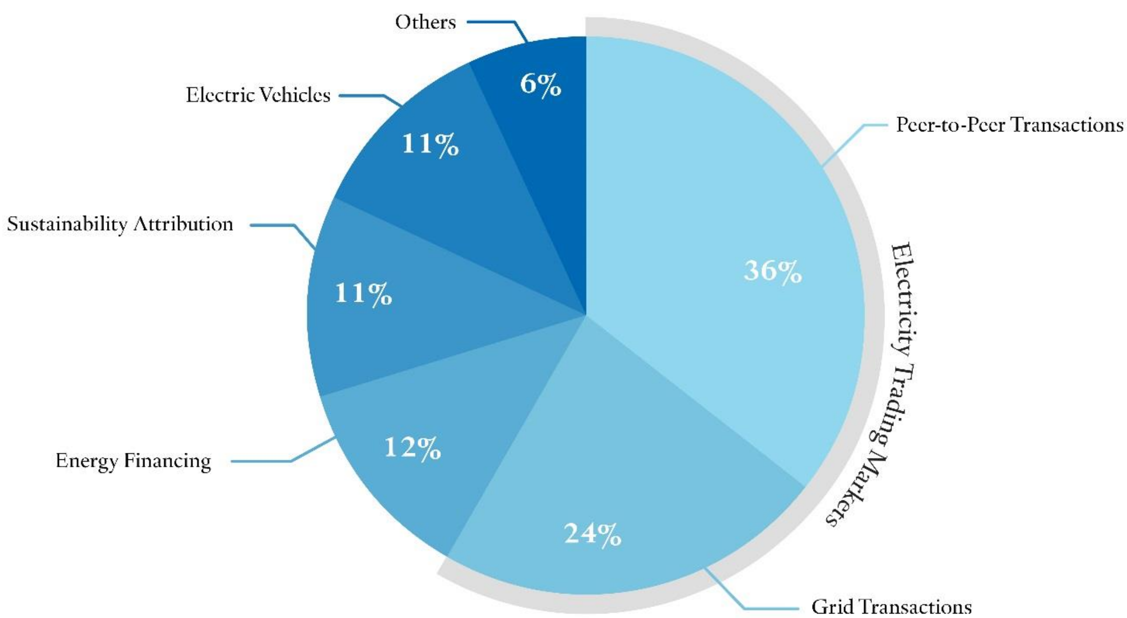
Figure 2. Geographic Distribution of Blockchain Initiatives in the Electric Power Sector



Source: Authors.

Finally, the applications of blockchain to the electric power sector are extremely diverse. Most can be classified into one of four broad categories (the category electricity trading markets is divided into the subcategories peer-to-peer transactions and grid transactions); a miscellaneous category covers the long tail of niche applications (see figure 3).

Figure 3. Blockchain Initiatives in the Electric Power Sector, by Category of Application



Source: Authors.

ELECTRICITY TRADING MARKETS

While the original application of blockchain was to facilitate the trading of cryptocurrencies, blockchain could also be used to facilitate the trading of electricity. Within this category, two camps have emerged: some initiatives aim to use blockchain to fundamentally reimagine the existing electric power system while others seek to incrementally improve it.

Peer-to-Peer Transactions

The most intuitive—and popular—application of blockchain to the electric power sector is to turn the electricity grid into a peer-to-peer network for customers to trade electricity with one another, for example, by buying and selling excess rooftop solar power.[25] Yet a truly decentralized, peer-to-peer trading network that upends the existing centralized grid is unlikely to materialize in industrialized countries in the next decade, notwithstanding the ambitions of several blockchain start-ups. In fact, many of these ventures rely heavily on today's grid. They might market themselves as peer-to-peer networks, but rather than enabling neighbors to actually trade power with one another, these ventures continue to use the existing distribution grid and merely conduct virtual transactions that do not change the physical flow of electricity. This may be just as well because the existing grid provides reliability and monetary benefits that are difficult to replicate in a true peer-to-peer network.

Still, even if blockchain does not replace the grid, it could enable more participants to trade electricity. For example, Vattenfall, the largest Nordic utility, is running trials in which it uses a private blockchain network to record electricity transactions in which department stores or even individual homes can sell electricity generated by distributed batteries or solar panels; previously, such transactions would have been prohibitively expensive and time-consuming to process.[26] And in areas of the developing world where electricity grids can be unreliable or nonexistent, opportunities exist for true peer-to-peer grids to emerge from the power vacuum. For example, the start-up ME SOLshare is connecting homes in Bangladesh so that they can trade excess energy from rooftop solar panels.[27]

Grid Transactions

A range of other electricity trading applications that are less radical than a truly decentralized peer-to-peer network are more likely to gain commercial traction—and support from incumbent utilities and regulatory authorities. These "grid transactions" relate to electricity trading in the context of an electric power system in which the power grid remains integral, even if its form and function changes substantially.

For example, Enel, a large European utility, is spearheading the Enerchain project to use blockchain to enhance existing wholesale electricity markets. In such markets, owners of large power plants sell bulk quantities of power to utilities and retailers that then sell the power to end users. Currently, these markets require a centralized entity running proprietary software to mediate each electricity transaction, which is both time-consuming and expensive. If these markets listed and cleared transactions on a blockchain network, however, transactions could be validated quickly and cheaply. In addition, the transaction data would be transparent for all market participants to access, enabling more efficient trading. Finally, these wholesale markets could broaden their pool of participants because a blockchain network can cope with a multitude of smaller transactions that would overwhelm a centralized system. As a result, businesses and even households could participate, selling their excess distributed generation into the market and responding to prices that reflect the grid's needs at each moment.[28]

In addition to enhancing the existing wholesale market, blockchain technology could underpin new markets that marshal distributed energy resources to help balance the grid. Today's wholesale markets can effectively set prices for bulk quantities of power, based on the customer demand in a particular region and the transmission capacity to transport power from the plants that bid into the market. But on the more local scales served by the distribution grid, no such market exists that takes into account instantaneous differences in customer demand among neighborhoods or constraints on local distribution capacity. To date, utilities have invested in costly infrastructure upgrades, such as new electrical substations, when the existing distribution grid cannot meet changing local needs. But as the costs of distributed energy resources—from solar panels to batteries to fuel cells—fall, it would be more sensible to harness such resources, whether situated on a customer's premises or on the distribution grid managed by a utility. Dispatched effectively, these distributed energy resources can defer the need for expensive infrastructure upgrades to serve communities and can even help keep the overall electricity grid in balance by stabilizing important parameters such as the grid's frequency and voltage.[29]

New so-called distribution markets could make this possible. Various jurisdictions, from South Australia to New York, are experimenting with these markets. In such markets, customers could buy or sell energy at time-varying prices based on their location. In addition, customers could provide services such as voltage support to the grid, also in response to granular price signals. Customers might employ smart software agents to act on their behalf and optimize their energy production and consumption based on market signals. And if they signed up with third-party aggregators, customers could pool their resources—offering to the grid the services of a so-called virtual power plant—that could help the overall system keep supply and demand in balance even with an influx of intermittent renewable energy on the grid.[30]

Blockchain networks could be an important component of enabling such distribution markets. These markets would need to process far more transactions than wholesale markets currently do, and recording those transactions on a blockchain ledger could enable rapid, cheap, transparent, and secure transactions. Moreover, smart contracts encoded into the blockchain ledger could automatically trigger transactions when certain conditions are met—for example, customers might offer to charge their batteries with excess electricity from the grid when the instantaneous compensation offered for providing charging services exceeds their preprogrammed threshold—facilitating efficient trading.

Still, many other advances will be needed on top of a blockchain infrastructure to realize distribution markets. Setting granular prices in such a market and regularly updating them will require a utility (or some other entity tasked with managing such a market) to install an array of sensors on the distribution grid, deduce the constraints faced at each location in the network, and perform intensive computations to determine real-time prices for the marketplace. Indeed, Australia's experimental Decentralized Energy Exchange project is focused on solving these pressing technical challenges first. The project's sponsors remain noncommittal on whether the platform will ultimately record transactions on a blockchain.[31]

ENERGY FINANCING

The use of blockchain and cryptocurrencies to raise funds for energy projects comprises the second largest category of initiatives to apply blockchain to the electric power sector. This category does not include start-ups that made an ICO to raise funds to then develop, say, a peer-to-peer trading platform. Rather, this category comprises ventures focused primarily on using cryptocurrencies to raise funds for energy projects (which tend, overwhelmingly, to be clean energy projects).

For example, WePower is a start-up conducting a demonstration project in Estonia to raise funds for renewable energy projects through cryptocurrency sales. To raise the majority of funds for a wind farm or solar park, WePower will seek traditional debt and equity financing just as any project developer would. But a minority of the project's funding would come from the sale of WePower's new cryptocurrency token, enabling anybody to participate in financing a new renewable energy project. The sale of the tokens would be recorded on WePower's blockchain ledger, and then token owners would be entitled to trade their tokens—over the blockchain network—for discounted electricity generated by the project once it is in operation.[32]

In this way, blockchain networks could make it easier for renewable energy projects to raise funds. They may broaden the pool of potential investors in renewable energy projects by enabling a multitude of smaller investors to supply capital. If a project developer can crowdsource a fraction of a project's financing by using such a network, that developer might be able to more easily persuade traditional investors to provide the balance of required investment. Still, it is unclear whether such a decentralized network is actually necessary to supply the funds needed for renewable energy generation to grow briskly. The cost of solar and wind projects has fallen steeply, and large institutional investors and major corporations are becoming increasingly comfortable with investing in renewable energy projects. Blockchain funding ecosystems might enable smaller investors and individuals to invest in projects to which they otherwise would lack access, but the societal benefits of doing so are not obvious.[33]

SUSTAINABILITY ATTRIBUTION

One of the most immediate applications of blockchain to electric power is its use to record and trade attributes of sustainability. Examples of such attributes include whether a unit of electricity is renewable and how much emissions resulted from its production. Currently, systems to track such attributes are centrally managed, complicated, and prone to fraud or errors. Moreover, the compartmentalization of platforms prevents seamless trading of attributes across regions. A decentralized blockchain network could enable transparent, accurate, and frictionless tracking and trading of these attributes, which would accelerate clean energy deployment and carbon emissions reduction.[34]

For example, the Energy Web Foundation's Origin application uses a blockchain to track electricity generation down to the kilowatt-hour and to record attributes such as the carbon emissions associated with power production. Doing so could enable more accurate calculation of carbon offset credits, which offer a mechanism to trade credits for carbon emissions reduced to balance out emissions created elsewhere, for owners and consumers of low-carbon electricity. Recognizing this potential, several utilities and firms, including Engie, Microsoft, and Singapore Power, are participating in pilot projects that use Origin.[35]

If these projects can be scaled up, then governments might become better equipped to regulate carbon emissions. To date, jurisdictions that have enacted carbon pricing policies have struggled to accurately track and record emissions. In the future, governments might use distributed ledgers to record and trade the carbon emitted from producing, transporting, and using energy. Various organizations—from IBM to an entity called the Russian Carbon Fund—are developing blockchain networks to record carbon attributes.[36]

ELECTRIC VEHICLES

The line between the electric power and transportation sectors is blurring as a result of the rising popularity of EVs. Such vehicles, however, still face substantial barriers to customer adoption—in particular, a scarcity of public charging infrastructure can dissuade potential buyers. Blockchain networks that enable private owners of charging infrastructure to seamlessly sell charging services to EV owners could improve the appeal and uptake of EVs.

For example, the Californian start-up eMotorWerks and the German utility-backed start-up MotionWerk have partnered on a pilot project in California to create a marketplace for EV charging. The initiative would enable households that own chargers to rent those to EVs, in a fashion similar to how a homeowner might rent a room to a guest via Airbnb. The start-ups reckon that a blockchain network can facilitate a large number of small transactions of fractional units of electricity and do so swiftly, securely, and transparently.[37]

Currently, firms struggle to keep down the costs of building and maintaining charging infrastructure as well as the cost of processing each charging transaction. If a blockchain network can reduce transaction costs by enabling EVs to charge using underutilized chargers already installed in residences or businesses, one of the largest barriers to EV adoption—a lack of available chargers to support travel—could erode. Beyond the coming years, blockchain networks could facilitate even more exotic charging transactions. For example, inductive chargers installed below roads could wirelessly charge vehicles stopped at a traffic light, with smart contracts automatically triggering small and swift transactions that are recorded on a blockchain ledger.[38] Finally, smart contracts could also enable EVs to charge up or discharge based on the grid's needs, enabling the vehicles to act as mobile batteries and to help stabilize the grid while netting their owners income in the process.[39]

OTHER APPLICATIONS

Most of the initiatives that fall outside the aforementioned categories have aimed to use blockchain to manage a large collection of assets. For example, the Finnish start-up Fortum aims to help electricity customers manage a range of internet-connected appliances. By managing and recording the energy use of appliances, such as heaters, in response to price signals from the grid, it aims to save customers money. (Still, for customers to actually harness their appliances in service of the grid's needs will require the creation of a distribution market and a system operator that sets granular prices.)[40]

Some utilities are also seeking to use blockchain networks to better manage their assets. For example, the start-up Filament is working with an Australian utility in the Outback to install sensors and record data about the weather and the health of grid infrastructure on a blockchain network, enabling the utility to improve its maintenance efforts.[41] And in the United Kingdom, the electricity regulator Office of Gas and Electricity Markets (OFGEM) is seeking to register customers' electricity meters as digital entities on a blockchain network. The goal is to enable customers to rapidly switch retail electricity providers—currently the switching process takes up to three weeks—by enabling swift and seamless transactions between customers and the retailers of their choice.[42]

Finally, some initiatives have sought to apply blockchain technology to enhance the cybersecurity of electric power systems. For example, a joint initiative of Siemens and U.S. government entities including the Departments of Energy and Defense is conducting a pilot demonstration of using the cryptographic algorithms that underpin blockchain to secure critical power sector infrastructure and prevent unauthorized breaches.[43]

Lessons From Three Case Studies of Application of Blockchain to Energy Trading

Examples of the most popular blockchain application—electricity trading—can clarify the limits to what new ventures can hope to accomplish in the coming years and how far they can go toward fundamentally altering electric power systems in coming decades. Three promising start-ups operating around the world are taking distinct approaches to facilitate energy trading over blockchain networks.

These examples reveal three lessons. First, although all of these start-ups aim ultimately to upend the conventional model of the electric power system, each is taking an incremental path and starting with modest goals. Second, achieving more than their initial, modest goals will require these start-ups to partner with incumbent utilities and regulatory reforms—each start-up alone is unlikely to transform the power sector. And finally, blockchain technology is only one component of the products that these ventures aim to launch; in other words, a blockchain network itself is less of an instant solution and more of an enabling platform that can complement a suite of other digital technologies.

LO3: THE BROOKLYN MICROGRID

The start-up LO3 Energy is setting up pilot projects around the world to demonstrate peer-to-peer electricity trading. Its most high-profile project is the Brooklyn Microgrid. The project's goal is to network thousands of Brooklyn residents in a self-sufficient microgrid, which is a small electricity network with its own sources of supply that can function independently of the main grid. Such a microgrid could improve the resilience of electricity supply to Brooklyn residents in the face of natural disasters that might cause the main grid to shut down. Moreover, by efficiently harnessing distributed generation sources such as solar panels, the microgrid could theoretically require less expensive infrastructure to produce and deliver energy within Brooklyn, reducing the bills of customers who currently pay high rates to cover their share of the costs of the main grid. To enable customers to efficiently use their distributed energy resources, LO3 is developing a blockchain platform to facilitate peer-to-peer energy trading.[44]

The initial version of the Brooklyn Microgrid is a far cry from LO3's ultimate vision. The pilot project comprises fewer than sixty prosumers. A larger number of participants can virtually trade electricity with one another, but they are not physically connected by a microgrid. Rather, most of the project's participants simply continue to use the main grid. When two participants "trade" electricity and one pays the other, the physical flow of electricity remains unchanged—for example, one participant feeds excess solar power back into the distribution grid, and the other participant consumes electricity from the grid. In fact, the participants cannot even transact electricity, because the utility has a monopoly over electricity sales, and instead can only trade renewable energy certificates.[45]

As a result, the first iteration of the Brooklyn Microgrid does not provide resilience, cost, or sustainability benefits. (LO3 argues that some customers can reduce their costs by selling excess distributed energy through the virtual microgrid, and this might induce the deployment of additional rooftop solar panels. But at a system-wide level, this practice is unlikely to reduce costs or carbon emissions.[46]) Importantly, using a blockchain ledger to facilitate energy trading is only one component of implementing a microgrid. Microgrids also require both software and hardware to keep the system in balance and interact with the main grid.[47]

For LO3 to achieve more of its vision will require it to collaborate with utilities and regulators. It hopes to work with the New York utility Con Edison to present Brooklyn Microgrid participants with a single bill that integrates their transactions with other participants as well as their cost of service by the utility. LO3 also hopes to convince regulators to allow it to legally broker sales of electricity among project participants. It will be several years before the company can construct a physical microgrid that can operate independently from the main grid, and doing so will almost certainly require the cooperation of the utility and state authorities.[48] Recognizing this, LO3 has sought industry partners around the world. For example, in South Australia, it has partnered with an authorized energy supplier and is working with regulators to set up an energy trading platform similar to the Brooklyn Microgrid.[49]

GRID+: WHOLESALE PRICING FOR RESIDENTIAL CUSTOMERS

The start-up Grid+, based in Texas, is using blockchain to give residential customers access to wholesale markets to which they are not ordinarily exposed. Owners of power plants, utilities, and large retailers that buy and deliver energy are normally the participants in wholesale markets, in which only large volumes of electricity are traded and the price fluctuates in real time. Residential end users typically pay a flat retail rate, which is split between the average cost of wholesale electricity and the cost of the grid infrastructure to deliver that electricity. If residential customers were exposed to time-varying electricity prices, they could intelligently adjust their power consumption over the course of a day to shave part of their electricity bills.[50]

To accomplish this, Grid+ sells customers tokens of a proprietary cryptocurrency. Customers can then use tokens to buy electricity at wholesale rates, with the transactions recorded on a blockchain ledger. Grid+ provides this service by aggregating its customers' purchases of electricity and placing larger purchases directly in the wholesale market. And because Grid+ requires its customers to prepay for cryptocurrency tokens to procure wholesale electricity, Grid+ is able to save money while other retailers take on the credit risk of customers who may not pay their bill after consuming electricity.[51]

Although Grid+ uses the Ethereum blockchain as its transaction processing platform, blockchain technology is only a small component of the company's business model. Grid+ also markets a smart software agent that opportunistically purchases wholesale electricity on the customer's behalf and optimizes the customer's appliances to minimize real-time energy costs. And the blockchain is likely less important to holding down costs than the prepayment scheme that Grid+ uses.

The company also is far from realizing its ultimate vision, which is to help customers manage their entire electricity bill, trade electricity with one another, and deploy their distributed energy resources to help balance the grid. Currently, Grid+ can only help customers save money on the wholesale electricity supply component of their bill, whereas the delivery charge component—which is often higher—remains unchanged. Eventually, the company hopes to help customers respond to time-varying price signals for distribution-level energy services, but doing so will require the creation of a distribution market and the cooperation of utilities and regulators.

ELECTRON: MULTI-SIDED FLEXIBILITY MARKETS

The start-up Electron, based in the United Kingdom, is exploring different applications of blockchain to the power sector. Its focus, however, is on creating a marketplace for flexibility in the production and use of electric power. In this marketplace, end users of electricity, such as households, could reduce their instantaneous energy consumption—for example, by reducing the usage of their smart appliances—for a price.

This marketplace could be classified as a distribution market, described earlier. Electron emphasizes the ability of its marketplace to match multiple buyers with multiple sellers of flexibility. For example, multiple customers in a community might all turn down their air conditioners and be compensated through a combination of payments from the distribution utility (which might have observed local congestion in the distribution network near those customers), the national grid operator (which might have observed overall system demand in excess of supply), and an energy retailer (which might have wanted to avoid procuring expensive power from the wholesale market at that instant). This approach might be much cheaper for the overall electric power system than would reducing the power output of a centralized power plant that is located far away from the part of the network that needs relief and that would incur costs to adjust its output.[52]

A blockchain network could help Electron process multi-sided transactions swiftly, transparently, and without hefty transaction fees. Recognizing that a range of different partners will be needed for its marketplace to gain scale and acceptance, Electron has aggressively courted a diverse group of companies, from utilities to engineering firms, to collaborate on this initiative. Moreover, the start-up has secured a government grant to execute a small-scale demonstration.[53]

The company is proceeding incrementally. In 2018, it plans to facilitate single trades between two parties before broadening its marketplace and implementing location-dependent pricing. And for its marketplace to succeed, Electron will need to develop technologies beyond just the underlying blockchain platform. Recognizing that blockchain is just the foundation that can facilitate other innovations, Electron's cofounder suggested that in fifteen years, "we won't be talking about blockchain anymore; we'll be using it without realizing it."[54]

Recommendations for Policymakers

Blockchain could be a valuable tool to contend with the increasingly complex electric power sector, and it could advance public policy objectives such as making electricity cleaner and more affordable, and the power system more resilient. Prospects for harnessing blockchain's potential heavily depend on policy decisions, and policymakers at the state and federal levels should respond to the hype over blockchain with prudence and preparation.

INVEST IN UNDERSTANDING BLOCKCHAIN AND ITS REGULATORY INTERSECTIONS

Blockchain is a foreign concept for most policymakers in the electricity sector, who often lack the right resources to understand what blockchain is, how a particular application might advance public policy objectives, and how blockchain networks should be regulated.[55]

A global push to enact data privacy regulations makes it particularly urgent that policymakers understand the intersection of blockchain and privacy. For example, the European Union's General Data Privacy Regulation, which came into force in May 2018, requires in some cases that personal data be anonymized or erased, for example, to comply with an individual's right to be forgotten. But whether blockchain records can be truly anonymized remains unclear; at best, an individual's data might exist on a blockchain under a pseudonym.[56] Moreover, because distributed ledger technology is by design immutable, data stored on it is difficult to erase.[57]

Sound policy will enable the electric power sector to harness the potential of blockchain while safeguarding data privacy. Policymakers should convene representatives from academia and industry to explain to them the basics of blockchain and its potential applications. Electricity regulators in the United Kingdom have proactively organized such gatherings, and policymakers in attendance have written up their insights in an accessible format to share with colleagues.[58] Regulators in the United States would benefit from similar convening. Recognizing this, the state of Illinois has established a Legislative Blockchain and Distributed Ledger Task Force.[59]

SUPPORT THE DEVELOPMENT OF BLOCKCHAIN STANDARDS IN THE ELECTRICITY SECTOR

At present, the growing multitude of initiatives with their own proprietary platforms could impede prospects for blockchain to achieve scale. Yet the promise of blockchain is to enable efficient transactions among a vast array of network participants. A set of standards ensuring that different blockchain platforms are interoperable could speed the commercialization of blockchain technology.

One of the first such efforts from the U.S. government, an interagency report published by the National Institute of Standards and Technology (NIST), provides an audit of blockchain applications but commits only two paragraphs to their possible use in the electricity sector.[60] NIST, which has a history of pioneering work in cryptographic standards dating back to the 1970s, should go further.[61] A useful first step could be convening stakeholders working on various application types to identify where common standards—such as for blockchain and protocol types—might be feasible, constructive, or impractical. In 2007, Congress passed the Energy Independence and Security Act that entrusts NIST with "primary responsibility to coordinate development of a framework that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems."[62]

Moreover, national laboratories such as the National Renewable Energy Laboratory should continue to assist industry consortia, such as the Energy Web Foundation, to develop private standards. These standards might address common protocols that ensure interoperability of private blockchains or might alternatively seek to create a template for certain smart contract types. Such efforts can help the United States, where the electricity landscape is fragmented, to keep pace with blockchain hubs in Europe, where fewer utilities and regulators have made early adoption of blockchain easier.[63]

In supporting the development of standards, policymakers should not show arbitrary preference to one firm's technical standards over another's. Rather, policymakers should support the development of open-source platforms that foster competition among multiple firms but ultimately pave the way for interoperability.

SET UP REGULATORY SANDBOXES TO ENABLE DEMONSTRATION PROJECTS

Other countries are experimenting with blockchain projects in the electric power sector often by relaxing electricity regulations at a small scale to foster innovation. This approach is sometimes called creating a regulatory sandbox, in which new ventures can test their ideas without affecting the bulk of the electricity system. For example, within a restricted geographic area, a sandbox might offer ventures relief from regulatory reporting requirements or legally ensure that a pilot project can operate, thereby making it possible for a start-up to raise private funding. National electricity regulators in Singapore and the United Kingdom have both pursued this approach and attracted prominent blockchain start-ups to pilot their ideas in their jurisdictions.[64]

Some U.S. states are following suit; more should do so. For example, the New York State government has encouraged firms to pursue small-scale demonstration projects applying a range of technologies—not limited to blockchain—under less restrictive regulations.[65] Such high-profile demonstration projects could provide an example to be scaled up at a later date. Equally important, this approach limits any failures of an experiment to one area. Insofar as blockchain can facilitate the more efficient operation of the electric power system—reducing costs, improving reliability and resilience, and limiting emissions—it deserves to be tested.

Conclusion

As electric power systems around the world rely more heavily on intermittent renewable energy, distributed energy resources, and sophisticated digital technologies, the industry will need to cope with rising complexity. Blockchain technology has the potential to help manage that complexity. The rise in value and popularity of cryptocurrencies has demonstrated that blockchain can be used to underpin a vast, distributed network that records transactions swiftly, immutably, and transparently. Now, substantial investment is flowing toward ventures that apply blockchain technology to the electric power sector. These ventures are being pursued by a diverse range of actors around the world, from start-ups to utilities to governments.

However, blockchain's potential in the electric power sector should not be overstated. Many blockchain ventures market a radical vision of the future in which centralized utilities are replaced with grassroots networks of peer-to-peer electricity trading. For the foreseeable future, those radical applications are unlikely to meaningfully change the electric power sector. Rather, initiatives that seek to partner with, rather than replace, incumbent firms and make incremental improvements within the existing model of the electric power system are most likely to gain commercial traction.

Policymakers should pay attention to the application of blockchain to the electric power sector. They should endeavor to understand the technology, support the development of blockchain standards in the electricity sector, and allow innovation to flourish by setting up regulatory sandboxes that permit demonstration projects.

Blockchain does not singularly address the various challenges that the electricity sector faces, but it should be one of a portfolio of technology options to address those challenges. And its potential as a platform technology might be transformative. Policymakers in the United States should watch this technology carefully and guide its progress and application.

Appendix: Listing of Blockchain Initiatives and Actors

The tables below organize our survey of actors involved in blockchain initiatives in the electricity sector, broken into start-ups, utilities, and governmental actors. The initiatives they are pursuing fall into the following categories of applying blockchain to the electric power sector:

- *Peer-to-peer transactions:* Applications of blockchain networks that enable customers to trade electricity, such as that resulting from excess rooftop solar generation, with one another directly, bypassing the centralized electric power system
- *Grid transactions:* Applications of electricity trading that continue to rely on the electricity grid, including in existing wholesale markets or new markets, such as distribution and flexibility markets
- *Energy financing:* Applications that use blockchain networks and/or cryptocurrencies to finance energy projects
- *Sustainability attribution:* Applications that are aimed at tracking and trading attributes of sustainability associated with electricity production, including renewable energy credits and carbon credits
- *Electric vehicles:* Applications that assist the management of, and payment for, electric vehicle (EV) charging
- *Others:* Applications that do not fit in the other categories, including asset registration and cybersecurity

In addition to the start-up, utility, and governmental actors listed in tables A1 through A3, many of the significant developments in the application of blockchain technology to the power sector are coming from consortia of different institutions, many of which involve actors from across tables A1, A2, and A3. Currently, the most prominent of these consortia are:

- *Energy Web Foundation (EWF).* EWF is a consortium funded through contributions by affiliates that include a wide range of utility, NGO, industrial, and start-up entities, such as Exelon, Electron, PG&E, Shell, and Tokyo Electric Power Company. It is working to develop its own open-source energy-focused blockchain platform (Energy Web Platform) on which various practical applications and programs can be developed. EWF is simultaneously working on designing new energy market models that would more fully leverage the Energy Web Platform and its potential.

- *Enerchain.* Enerchain is a Europe-based consortium that was started in May 2017 with twenty-three participants and has since grown to more than forty participants, including E.ON, Engie, Statkraft, and Vattenfall. It is working to develop blockchain-based energy trading and transaction platforms that can make trading of nonstandard commodities and derivatives faster, cheaper, and easier. It is working with Ponton, a German enterprise software provider, to apply the Enerchain platform to business cases such as the development of traded energy products with smart contract functionality and the optimization of grid management processes.

- *Enterprise Ethereum Alliance (EEA).* EEA connects large and small companies, academics, and technology firms with blockchain developers in order to develop "enterprise-grade" software that can run on the Ethereum blockchain. It has an energy-specific working group on the following focus areas: oil and gas, mining, refining, trading, utilities, and grids. Examples of such infrastructure being developed by member entities include Microsoft's partnership with SunContract and Samsung's ADEPT Internet of Things appliance platform.
- *Hyperledger.* Hyperledger, hosted by the Linux Foundation, helps members to create blockchain-based platforms and applications that can span different industries, including energy. Examples of energy-related projects include IBM's piloting of tokenized carbon credits and SAP's partnership to supply technological expertise to Lition Energy, a licensed energy supplier in Germany attempting to use blockchain-based smart contracts to directly match producers and consumers.
- *Mobility Open Blockchain Initiative (MOBI).* MOBI is a more recent consortium, formed in May 2018, and comprising actors such as BMW, Ford, and Renault that are focused on using blockchain technology to improve the provision of mobility services. It plans to work on use cases, such as autonomous machine payments (for electric fuel) as well as carbon and pollution pricing.

Table A1. Start-Up Companies and Initiatives Utilizing Blockchain in the Energy Sector

Company	Country	Application Type	Blockchain	Blockchain Type	Description of Initiative
Aizu Laboratories	Japan	Grid transactions	Proprietary	Private	Software to record electricity transactions with blockchain-enabled systems
Bankymoon	South Africa	Peer-to-peer transactions	Bitcoin	Public	Smart meters for electricity grid to enable peer-to-peer transactions
BTL	Canada	Grid transactions	Interbit	Private	Platform for large-scale cross-border electricity trading with Wein Energy in Austria
CarbonX	Canada	Sustainability attribution	ERC20	Public	Peer-to-peer carbon credit trading platform
CLIMATECOIN	Switzerland	Sustainability attribution	ERC20	Public	Tokenized carbon credit market platform
Conjoule	Germany	Peer-to-peer transactions	Ethereum	Private	Local peer-to-peer marketplace that allows residential producers of renewable electricity to sell to homes and individuals
Consensys	United States	Peer-to-peer transactions	Ethereum	Public	Leading Ethereum network development organization whose energy working group collaborated on Grid+
Dajie	United Kingdom	Peer-to-peer transactions	ERC20	Public	Network in which consumers can trade in peer-to-peer electricity or redeem carbon credits
Drift	United States	Grid transactions	Proprietary	Private	Renewable energy market platform that connects individuals with wholesale renewable energy providers
Elblox	Switzerland	Peer-to-peer transactions	Ethereum	Private	Local peer-to-peer and retail electricity market platform
ElectriCChain	Andorra	Sustainability attribution	Ethereum	Public	Decentralized solar power generation auditing and data market platform
Electrify.Asia	Singapore	Peer-to-peer transactions	ERC20	Public	Energy trading platform that accommodates both peer-to-peer and retail transactions

Ethereum (ERC 20) denotes an initiative using the Ethereum platform and the ERC20 standard, a standard that enables an initiative to operate on its own token but still utilize the Ethereum network to validate transactions.

Company	Country	Application Type	Blockchain	Blockchain Type	Description of Initiative
Electron	United Kingdom	Peer-to-peer transactions	Ethereum	Private	Peer-to-peer energy trading platform that integrates shared registration for UK gas and electricity supply points
eMotorWerks	United States	Electric vehicles	Ethereum	Public	Peer-to-peer electric vehicle (EV) charging network through partnership with Share&Charge platform
Enbloc	United States	Peer-to-peer transactions	ERC20	Public	Peer-to-peer platform that allows residential producers of renewable electricity to sell to consumers
Energi Mine	United Kingdom	Sustainability attribution	ERC20	Public	Platform that allows entities to reward low-carbon activities with tokens redeemable for energy consumption
Energo	China	Peer-to-peer transactions	Qtum	Public	Platform for measurement, registration, transaction, and settlements for microgrid clean energy
Energy Blockchain Labs	China	Sustainability attribution	Hyperledger	Private	Decentralized carbon asset trading platform
Energy Web Foundation	Switzerland	Grid transactions	Ethereum	Public-Private	Blockchain-based energy applications and an open source IT infrastructure
Energy21	Netherlands	Grid transactions	Quasar	Private	Application that enables grid operators to set up community energy markets
EnLedger, Corp.	United States	Sustainability attribution	Tendermint	Public	Energychain Project allows for the issuance, tracking, and trading of renewable energy credits (RECs)
Everty	Australia	Electric vehicles	Ethereum	Public	Peer-to-peer EV charging network
Evolution Energie	France	Peer-to-peer transactions	Hyperledger	Private	Peer-to-peer energy trading platform
Freeelio	Germany	Other	Ethereum	Public-Private	Adaptive platform that coordinates demand response for connective household appliances

The Energy Web Foundation operates the Tobalaba platform, which mixes elements of a private and public blockchain.

Company	Country	Application Type	Blockchain	Blockchain Type	Description of Initiative
LO3	United States	Peer-to-peer transactions	Proprietary	Private	Platform for peer-to-peer electricity markets
M-PayG	Denmark	Energy financing	Proprietary	Private	Pay-as-you-go solar energy for households across the developing world
MITO	Russia	Sustainability attribution	ERC20	Public	Environmental accounting platform for carbon assets and liabilities
MotionWerk	Germany	Electric vehicles	ERC20	Public	Partnership with Slock.it on Share&Charge platform, which provides decentralized EV charging locations
MyBit	Switzerland	Energy financing	ERC20	Public	Crowdfunding blockchain platform that allows communities to purchase decentralized grids
NRG	Belgium	Peer-to-peer transactions	ERC20	Public	Joint industry-academic project that is building peer-to-peer microgrid markets in Belgium
Omega Grid	United States	Grid transactions	Proprietary	Private	Smart grid management platform for operators
Ponton	Germany	Grid transactions	Tendermint	Private	Operates Enerchain, a blockchain-powered wholesale electricity trading platform
Poseidon	Switzerland	Sustainability attribution	Stellar	Public	Platform for issuing, tracking, and trading carbon credits
Power Ledger	Australia	Peer-to-peer transactions	ERC20	Public	Integrated energy trading platform that allows for peer-to-peer transactions and wholesale market settlements
Prosume	Switzerland	Peer-to-peer transactions	ERC20	Public	Integrated energy crowdfunding and trading platform that is not limited to renewable sources
Pylon Networks	Spain	Peer-to-peer transactions	LiteCoin Fork	Public	METRON smart meter–integrated peer-to-peer renewable energy market platform

Company	Country	Application Type	Blockchain	Blockchain Type	Description of Initiative
Restart Energy	Romania	Energy financing	ERC20	Public	Franchising platform that allows token-holders to host and participate in virtual retail power companies
Slock.it	Germany	Electric vehicles	Ethereum	Private	Partnership with Motionwerk to develop the Share&Charge platform, which provides decentralized EV charging locations
Solar Bankers	Singapore	Peer-to-peer transactions	Sky Ledger	Public	Decentralized solar energy network based on the Skycoin blockchain
SolarDAO	Russia	Energy financing	ERC20	Public	Solar power crowdfunding platform
Sonnen	Germany	Peer-to-peer transactions	Hyperledger	Private	Virtual power plant platform focused on distributed energy storage
Spectral	Netherlands	Peer-to-peer transactions	MultiChain	Public	Partnership with Alliander to develop the Jouliette, an energy token used for local peer-to-peer energy trading
StromDAO	Germany	Energy financing	ERC20	Public	Decentralized autonomous organization that focuses on renewable energy assets and peer-to-peer trading
Sunchain	France	Grid transactions	Proprietary	Private	Distributed solar power storage for private prosumers
SunContract	Slovenia	Peer-to-peer transactions	ERC20	Public	Peer-to-peer retail energy transactions platform
Sunverge	United States	Grid transactions	Proprietary	Private	Virtual power plant platform that focuses on distributed energy storage
Swytch	United States	Sustainability attribution	ERC20	Public	Platform that tracks and verifies the impact of sustainability efforts, rewarding people and organizations that reduce carbon emissions with energy tokens
The Sun Exchange	South Africa	Energy financing	ERC20	Public	Solar panel purchase-and-lease platform emphasizing opportunities in sub-Saharan Africa

Company	Country	Application Type	Blockchain	Blockchain Type	Description of Initiative
ToBlockchain	Netherlands	Peer-to-peer transactions	Proprietary	Private	PowerToShare suite of solutions that facilitates peer-to-peer transactions and energy origin auditing
Ubitricity	Germany	Electric vehicles	Ethereum	Private	Mobile electricity meter that allows for trustless EV charging within smart grids
Veridium	United States	Sustainability attribution	Stellar	Public	IBM-partnered platform that issues, tracks, and trades carbon credit
Volt Markets	United States	Sustainability attribution	Ethereum	Private	Platform that issues, tracks, and trades RECs
Wanxiang BlockchainLabs	China	Electric vehicles	Ethereum	Private	Conglomerate-backed blockchain incubator that pursues charging/battery solutions
WePower	Lithuania	Energy financing	ERC20	Public	Renewable energy financing and power trading platform
XiWatt	United States	Energy financing	Ethereum	Public	Renewable energy asset crowdfunding and trading platform

Table A2. Blockchain Initiatives by Utilities

Utility	Country	Application Type	Description of Initiative
ACWA Power	Saudi Arabia	Energy financing	Adopting SolarCoin, a cryptocurrency that is rewarded to generators of solar power
Alectra Utilities	Canada	Peer-to-peer transactions	Creating system in which consumers can dispatch resources in real time to meet utility needs
Allgauer Uberlandwerk	Germany	Peer-to-peer transactions	Working with LO3 Energy to pilot virtual microgrid for energy marketplace
Alliander	Germany	Peer-to-peer transactions	Created Jouliette, a blockchain-based energy-sharing token that allows individuals and communities to easily manage and share locally produced energy
Alpiq	Switzerland	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Ameren	United States	Peer-to-peer transactions	Working with Omega Grid to implement blockchain-based grid balancing and settlement for electric utilities
Arge Netz	Germany	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Australian Gas Light Co.	Australia	Peer-to-peer transactions	Piloting peer-to-peer marketplace for residential solar electricity
Axpo	Switzerland	Peer-to-peer transactions	Launched peer-to-peer blockchain platform that allows consumers to buy electricity directly from renewable producers; joined Enerchain framework
BKW Energie (formerly Bernische Kraftwerke)	Switzerland	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Centrica	United Kingdom	Peer-to-peer transactions	Piloting local energy marketplace allowing peer-to-peer energy trading
Chubu Electric Power Company	Japan	Electric vehicles	Piloting blockchain-based electric vehicle (EV) charging service
Direct Energy	United States	Energy financing	Partnered with LO3 Energy to offer "micro-energy hedging" in energy markets
Dubai Electricity and Water Authority (DEWA)	United Arab Emirates	Electric vehicles	Launched Green Charger, enabling charging station operators to use DEWA's services

Utility	Country	Application Type	Description of Initiative
EDF Luminus	Belgium	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
ekWateur	France	Energy financing	Accepts SolarCoins, a cryptocurrency that is rewarded to generators of solar power
Elegant	Belgium	Energy financing	Accepts bitcoin for bill payments
EnBW	Germany	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Endesa	Spain	Energy financing	Joined Enerchain framework to conduct direct electricity trading between energy companies
Eneco	Netherlands	Grid transactions	Piloting a blockchain application to create a decentralized heating network in Rotterdam
Enel	Italy	Grid transactions	Joined Enerchain framework to conduct peer-to-peer trading in the wholesale energy market
Enercity	Germany	Energy financing	Accepts bitcoin for bill payments
Eneres	Japan	Peer-to-peer transactions	Piloting peer-to-peer marketplace for 1,000 households
EnergieSüdwest AG	Germany	Peer-to-peer transactions	Piloting an electricity trading platform for peer-to-peer trading with LO3 Energy
Enexis	Netherlands	Electric vehicles	Prototyping IOTA-enabled cryptocurrency transactions for EV charging
Engie	France	Sustainability attribution	Working with Air Products to certify renewable energy use in production processes
Enel	Italy	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
E.ON	Germany	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Equs REA Ltd.	Canada	Grid transactions	Launched system to record residential renewable energy production
Exelon	United States	Grid transactions	Joined the Energy Web Foundation

Utility	Country	Application Type	Description of Initiative
Fortum	Finland	Other	Enables consumers to control appliances
Iberdrola	Spain	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Korea Electric Power Corporation	South Korea	Peer-to-peer transactions	Piloting peer-to-peer electricity sales program
Leipziger Stadtwerke	Germany	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Marubeni	Japan	Energy financing	Piloting bitcoin payments
Origin	Australia	Peer-to-peer transactions	Piloting electricity trading platform with customers through partnership with Power Ledger
Pacific Gas and Electric (PG&E)	United States	Electric vehicles	Has approved eMotorWerks and Oxygen Initiative as vendors for its 7,500 EV charging station expansion plan
Rheinisch-Westfälisches Elektrizitätswerk	Germany	Electric vehicles	Joined Enerchain framework to conduct direct electricity trading between energy companies
Salzburg AG	Austria	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
SP Group	Singapore	Sustainability attribution	Launched blockchain-enabled platform to transact renewable energy certificates
Statkraft	Norway	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Stedin	Netherlands	Electric vehicles	Joined the Energy Web Foundation
Tavrida	Russia	Grid transactions	Partnered with blockchain firm Qiwi to allow for electricity transactions between power plants
Tennet	Germany	Electric vehicles	Developing blockchain-based system that integrates household batteries and charging for electric vehicles
Toyota Electric Power Co	Japan	Peer-to-peer transactions	Invested in Electron to create peer-to-peer energy marketplace
Uniper	Germany	Grid transactions	Joined Enerchain framework to conduct direct electricity trading between energy companies
Vattenfall	Sweden	Peer-to-peer transactions	Piloting Powerpeers, a marketplace for peer-to-peer energy trading; joined Enerchain framework
Verbund	Austria	Grid transactions	Partnering with Salzburg AG to create a peer-to-peer electricity trading platform; joined Enerchain framework
Vorarlberger Kraftwerke	Austria	Electric vehicles	Involved in MotionWerk blockchain wallet for EV charging
Wien Energie	Austria	Grid transactions	Piloting cross-border electricity trading platform with BTL; joined Enerchain framework

Table 3. Government-Level Regulatory Initiatives Utilizing Blockchain in the Energy Sector

Regulatory Body	Country	Application Type	Description of Initiative
Australian Energy Market Operator	Australia	Peer-to-peer transactions	Developing smart-metering and battery storage system to facilitate energy and water efficiencies among dispersed critical infrastructure
Australian Renewable Energy Agency	Australia	Peer-to-peer transactions	Enabling consumers and businesses to trade their own renewable energy with one another and with network companies
China State Grid Corporation*	China	Other	Tracking and storing data on consumers' power consumption and generation in a decentralized manner
Homeland Defense and Security Information Analysis Center	United States	Other	Developing blockchain cybersecurity technology to help secure distributed energy resources
Ministry of Micro, Small and Medium Enterprises	India	Energy financing	Using Ethereum blockchain to manage supply-chain logistics for renewable energy–powered textile looms
National Energy Commission	Chile	Other	Recording data from energy sector using the Ethereum network
National Grid United Kingdom	United Kingdom	Peer-to-peer transactions	Backing energy trading platform launched by Electron
National Renewable Energy Lab	United States	Peer-to-peer transactions	Partnering with BlockCypher to demonstrate transactions of distributed energy resources across multiple blockchains
German Ministry of Economic Affairs and Energy	Germany	Grid transactions	Piloting a large-scale decentralized and integrated platform for renewable generation, transmission, and distribution infrastructure
Office of Gas and Electricity Markets (OFGEM)	United Kingdom	Peer-to-peer transactions	Launched regulatory sandbox with a consortium of companies to trial a peer-to-peer trading platform
Pacific Northwest National Labs	United States	Other	Advancing a variety of potential applications for power grid management
Russia Carbon Fund	Russia	Sustainability attribution	Developing an audit system for climate projects with Ernst and Young
Singapore Energy Market Authority	Singapore	Peer-to-peer transactions	Launching a regulatory sandbox, modeled on OFGEM
Smart Dubai	United Arab Emirates	Peer-to-peer transactions	Developing smart energy systems using blockchain
South Korean Science Ministry	South Korea	Peer-to-peer transactions	Piloting a peer-to-peer electricity marketplace
Sustainable Energy Development Authority	Malaysia	Sustainability attribution	Invested in peer-to-peer marketplace project run by Power Ledger

** China State Grid Corporation could be considered both a utility and a government initiative given its unique, state-owned status.*

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