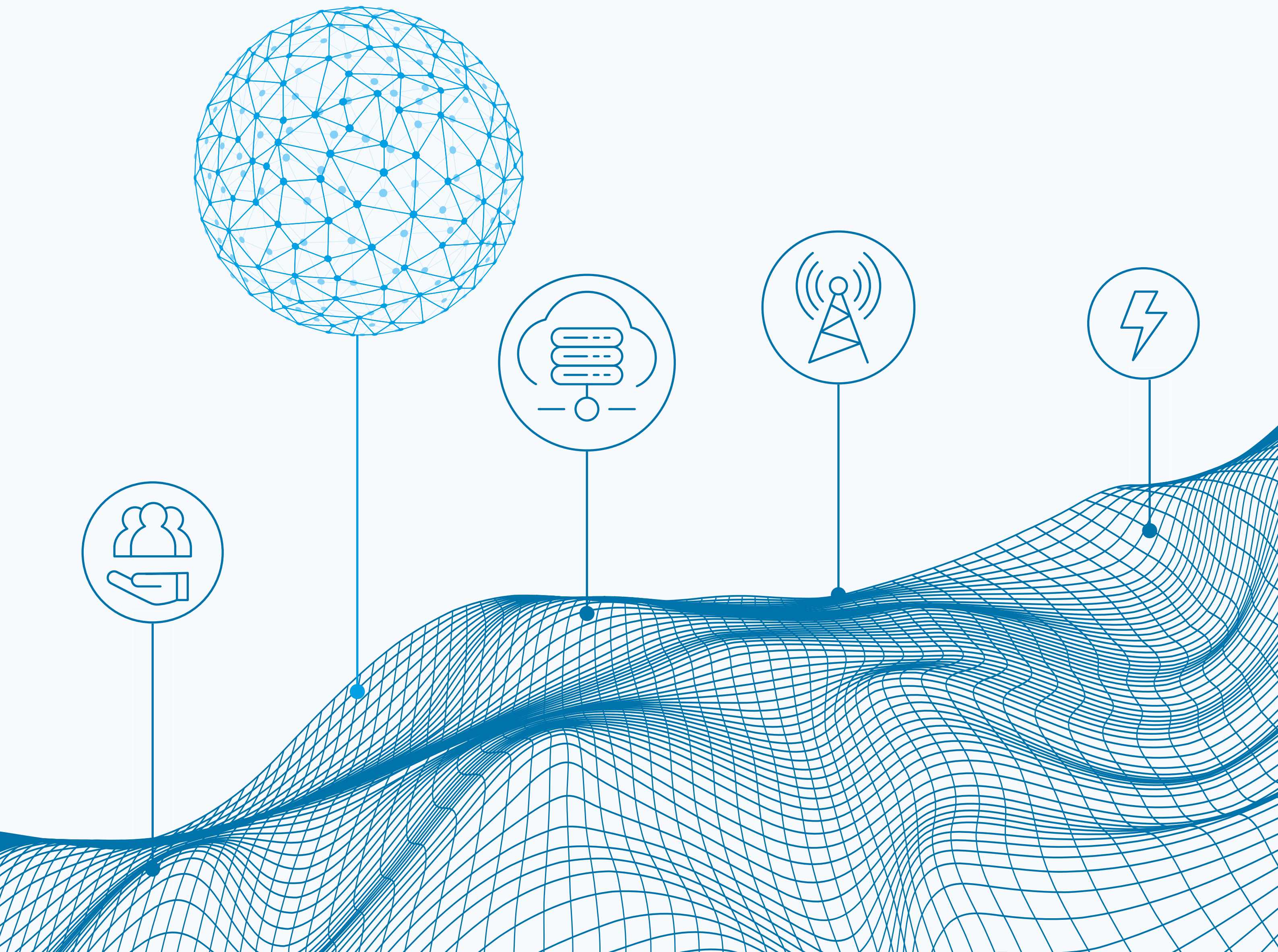
IRENA
International Renewable Energy Agency

BLOCKCHAIN

INNOVATION LANDSCAPE BRIEF



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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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Disclaimer

BLOCKCHAIN

Increased power sector complexity requires greater intelligence, transparency and automation. Blockchain can help.

WHAT IS BLOCKCHAIN?

Blockchain platforms are the base layer on which decentralised applications can be built. Through decentralisation, they can be used to securely record all transactions taking place on a given network without a central intermediary.
See boxes 1 through 4 for how the technology can impact the power sector.

1 HOW IT WORKS

BLOCKCHAIN enables the implementation of **SMART CONTRACTS**, self-executing programmes which can be used to better manage systems and integrate higher shares of renewables through automation.

$ ON

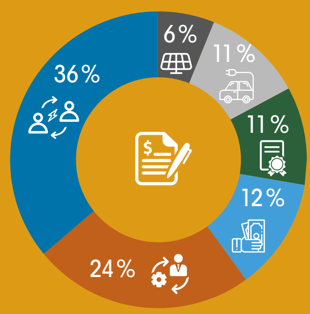
Smart contracts are set to self-execute when specific conditions are met, e.g. when peers trade electricity for payment.

2 POTENTIAL BENEFITS OF BLOCKCHAIN

- → Reduced transaction costs
- → Increased transparency
- → Increased security
- → Increased automation via smart contracts
- → Increased participation by new/more actors via decentralisation

3 KEY APPLICATIONS TO INTEGRATE RENEWABLES

- → Peer to peer power trade
- → Grid management and system operation
- → Financing renewable energy development
- → Management of renewable energy certificates
- → Electric mobility
- → Others



4 CURRENT SNAPSHOT

- → **189** companies working in blockchain in energy
- → **71** projects focused on blockchain in energy
- → USD **466** million invested in blockchain in power
- → About **50 %** of projects built on the Ethereum blockchain

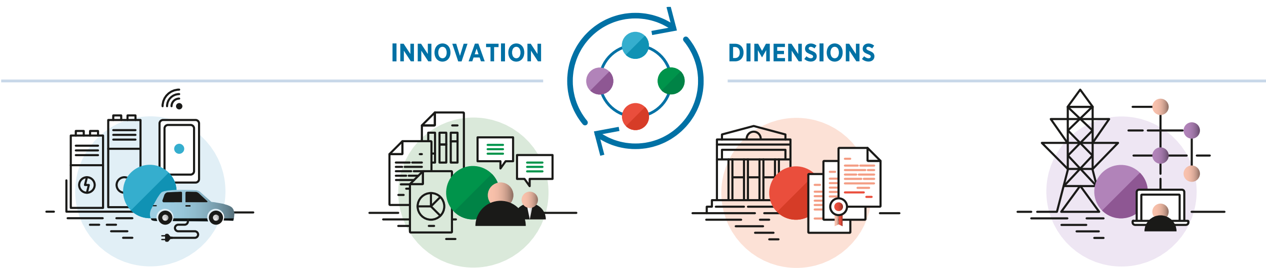
**as of September 2018*

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*, illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



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4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
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This brief provides an overview of blockchain[1] technology and its applicability in the power sector, with a focus on the means by which it can enable the integration of more renewable energy. With "smart contracts",[2] blockchain has the potential to play a major role in helping to integrate renewables by automating processes, increasing power system flexibility and reducing transaction costs. It can simultaneously accelerate the adoption of other technologies, such as storage and electric vehicles (EVs), leading to improved grid management and system operation.

With the relatively recent increase in power sector complexity comes a need for greater intelligence and transparency. Surging numbers of smart devices coming online are generating vast amounts of granular data – important fuel for burgeoning technologies, such as artificial intelligence, to increase the efficiency of power systems and reduce energy usage. New tools to manage all this data in a secure, efficient and transparent manner are being sought, and blockchain technology is already proving useful. New business models in the energy sector enabled by blockchain technology continue to emerge and evolve, with the spotlight currently on local peer-to-peer (P2P) and wholesale power trading as well as innovative means of project financing in developing countries, among others.

This brief is structured as follows:

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1 Blockchain is a specific type of distributed ledger technology (DLT), which utilises a chain of blocks as the underlying data structure. There are, however, multiple forms of DLT, such as: blockchains, directed acyclic graphs, hash graphs and distributed hash tables. In general, the term "blockchain" is used as a catchall for DLTs. This principle has also been applied to this document, as both terms are used throughout.

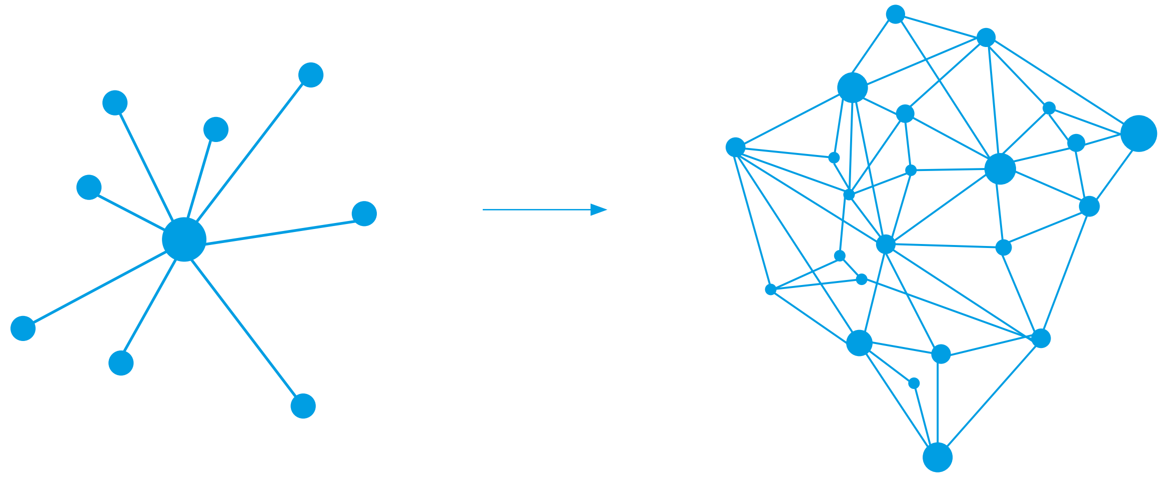
2 Contracts programmed to self-execute when specified conditions are met.

I. DESCRIPTION

Distributed ledger technology (DLT), such as blockchain, is a relatively recent technological innovation that has wide-ranging implications for many sectors. While the cryptographic technologies underpinning blockchains have been around for some time, their combination into a useful package was truly innovative. In the power sector, that combination matched with the proliferation of distributed energy resources and grid-interactive devices is what makes blockchain potential exciting. But what *are* blockchains exactly? Blockchains are essentially immutable digital ledgers that can be used to securely record all transactions taking place on a given network – once data is sealed within a block it cannot be changed retroactively. This includes not only financial transaction data, but almost anything of value.

The technology is enabling a new world of decentralised communication and co-ordination, by building the infrastructure to allow peers to safely, cheaply and quickly connect with each other without a centralised intermediary. Cryptography ensures security and data integrity, while privacy remains intact. Combined with an economic incentive framework also known as a consensus mechanism,[3] this allows for the peer-to-peer

Figure 1 Moving from a traditional centralised model with a trusted intermediary (left) to a decentralised, distributed model built on blockchain (right)



3 *A set of rules that decides on the contributions by the various participants of the blockchain. Proof of work is a common consensus algorithm used by blockchains such as Bitcoin and Ethereum, whereby "miners" solve complex cryptographic puzzles before they can publish new blocks to the chain.*

validation of transactions through enhanced security, better data management and increased ability to co-operate among multiple actors, while bypassing the need for a trusted, centralised intermediary to verify transactions.

In the power sector, blockchain technology offers many possibilities. It could pave the way for sophisticated networks that decentrally and democratically manage the entire distributed energy value chain in a more disintermediated[4] and efficient way (Figure 1). This includes the management of power generation and distribution, sales, billing, payments, innovative financing mechanisms, contract management, and trading and incentives.

This shift from centralisation to decentralisation gives rise to the potential for every participant in a network to transact directly with every other network participant without a third-party intermediary to validate and secure transactions, thus reducing transaction cost and time, and establishing the backbone for a new type of decentralised internet. Today, most blockchains are permissionless[5] public ledgers based on open protocols, such as Bitcoin and Ethereum, in which anyone can connect to the blockchain and participate. There are, however, a number of permissioned[6] blockchains currently in development, used primarily for enterprise solutions.

Importantly, blockchain technologies are still in their infancy, and therefore questions remain about security, scalability and governance. New projects based on blockchain aim to disintermediate: protection of personal data; electronic voting; cross-border micropayments; supply chain management; and electricity generation and usage, among others. These projects are built upon a wide range of protocols utilising a variety of consensus algorithms. However, blockchain is evolving, and new technologies are proving to be far more energy efficient, faster and more scalable than their predecessors. Many blockchains even allow for the coding of self-executing contracts, or "smart contracts", meaning digital contracts that are programmed to self-execute when specified conditions are met (*e.g.* if A receives X kilowatt hours [kWh], then B automatically receives Y monetary units as payment) – again, without the need for a centralised, trusted authority. This is a concept first pioneered by Nick Szabo in 1994 and employed by the Ethereum blockchain in 2013 (Blockgeeks, 2018).

With the increasing number of internet-connected smart devices, the surface area for cyberattacks is also expanding and growing power sector interconnectedness is exacerbating these security risks. Tools such as blockchain, due to its decentralised and cryptographically[7] secured nature, offer new means of securing networks and increasing transparency, thereby helping to reduce fraud and abuses of privacy which have become increasingly common.

The role of blockchain smart contracts in the power sector

The power sector is among those most discussed as being prone to disruption through blockchain integration. The highly centralised market structure and regulatory environment make power a highly suitable sector for the application of blockchain technology, as electrons can be traded instantaneously with minimal transaction fees in a decentralised network (*e.g.* from neighbour to neighbour), while payments can be processed simultaneously.

4 Disintermediation is the removal of intermediaries.

5 In a permissionless blockchain, anyone can join the network, participate in the process of block verification to create consensus and also create smart contracts. A good example of permissionless blockchain is the Bitcoin and Ethereum blockchains, where any user can join the network and start mining. These offer greater transparency and decentralisation than permissioned blockchains, but face greater challenges in terms of scalability and speed.

6 A permissioned blockchain restricts the actors who can contribute to the consensus of the system state. In a permissioned blockchain, only a restricted set of users have the rights to validate the block transactions. A permissioned blockchain may also restrict access to approved actors who can create smart contracts. Recent developments have seen permissioned blockchains such as Energy Web Chain emerge, which rely on proof of authority for consensus.

7 Cryptography is the practice of techniques for secure communication. It is a method of storing and transmitting data in a particular form so that only those for whom it is intended can read and process it.

With smart contracts, consumers are transformed into active participants in the market, able to buy and sell their electricity without involving a trusted authority or intermediary. Smart meter solutions can even immediately publish renewable generation data to the blockchain as the power is produced, and carbon reduction incentives, or green certificates, can be determined and earned instantly. Smart contracts enabled by blockchain, and used in concert with smart meter technology, offer a number of efficient, effective and affordable solutions to help transform the power sector, and may ultimately enable truly transactive energy systems (EWF, 2018a).

II. CONTRIBUTION TO POWER SYSTEM TRANSFORMATION

By acting as the foundational data layer on which information, value and electrons are exchanged, blockchain technology has the potential to play an important role in the transformation of the power sector, underpinning the applications that perform the optimisation and co-ordination. Its influence begins with niche uses and spreads with stakeholder awareness and acceptance.

Smart contracts are a key tool enabling the development of the blockchain initiatives presented in Figure 2. By automating the definition of rules and penalties relating to an agreement, while also automatically enforcing obligations, smart contracts have the potential to greatly reduce friction from the establishment and enforcement of contracts by removing the intermediary. This is accomplished while also integrating the security, transparency and immutability features that blockchain technology offers. Smart contracts work on the If-Then premise. An apt metaphor often used to describe these self-executing contracts is that of a vending machine, whereby your purchased item automatically arrives once you deposit payment and make a selection. In the case of smart contracts, the vending machine is the ledger and the products can be anything from kilowatt hours of electricity to real estate deeds.

Smart contracts built on blockchain can help modernise electricity grids by allowing a total system approach to be developed, enhancing the use of renewables, particularly hard-to-integrate intermittent sources, while improving operations and management of network assets. Lower costs, faster processes and greater flexibility are all possible through this shift in the underlying transaction model from centralised to decentralised.

In the not-too-distant future smart contracts might automatically buy and sell power from and to the grid based on real-time price signals, for homes and businesses equipped with the necessary software and smart meters. Furthermore, with hundreds of thousands of new devices connecting to the grid, a way is needed to co-ordinate them effectively and allow them to play their full role in balancing the grid. As the grid moves from a top-down centrally managed system to a bidirectional market with many more assets at the grid edge, co-ordination becomes key. Blockchain is a data management tool that can facilitate effective co-ordination between many actors, with low transaction costs.

Some of the transformative uses of blockchain possible in the power sector are presented below, emphasising the impact on power sector transformation and renewables integration.

Peer-to-peer power trade

With the potential for a decentralised model based on blockchain to reduce transaction costs, smaller electricity producers could sell excess renewable energy to other network participants, thus, in theory, bringing down prices through increasing competition and grid efficiency. Trusted third parties, such as retailers, may play a much smaller role in a distributed P2P model, and smart contracts will automate processes that previously

Figure 2 Blockchain initiatives in the power sector

Note: Data as of July 2018.
Based on: Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems.

required manual work and multiple parties (HBR, 2017). With smart contracts, trades can be made automatically using price signals and real-time renewable energy production data throughout the network.

Companies are now working on intelligent grids, which use digitalisation and smart contracts to automate the monitoring and redistribution of microgrid energy. By acting as the foundational data layer, DLTs such as blockchain can also assist in achieving the localised goals of power systems, such as the optimisation of distributed energy resources in microgrid networks. Companies such as Power Ledger and LO3 Energy, and research initiatives such as The Energy Collective, have been experimenting with local microgrids, allowing neighbours to make virtual electricity trades using the local grid and potentially allowing consumers to own shares in nearby solar farms, selling their share of the power generated on the open market.

The ability to freely sell one's generated power at market rates to a network of peers provides incentives for increased adoption of distributed renewables. These granular transactions are being enabled through blockchain, but barriers to widespread adoption exist, with the lack of a consistent regulatory environment playing a large role. Energy Web Foundation (EWF) – in collaboration with large energy companies and start-ups – is developing an open-source, scalable blockchain platform specifically designed for the energy sector's regulatory, operational and market needs. The objective is to promote energy sector innovation and accelerate the transition to a decentralised, democratised, decarbonised and resilient energy system (EWF, 2018b).

Grid management and system operation

Blockchain technology allows electricity networks to be more easily controlled, as smart contracts would signal to the system when to initiate specific transactions. This would be based on predefined rules created by the platform, designed to ensure that all power and storage flows are controlled automatically to balance supply and demand. For example, whenever more variable renewable energy is generated than needed, smart contracts could be used to ensure that excess electricity is diverted into storage automatically. Conversely, the electricity held in storage could be deployed for use whenever the generated power output is insufficient. In this way, blockchain technology could directly control network flows and flexibility options, avoiding curtailment of solar and wind energy.

In addition, the exchange and transaction of electricity can be optimised over a wider network, which would help bring down costs while increasing the integration of variable renewables. When renewable energy sources in a fixed geography are unreliable, load sharing over a wider area reduces the variability and the need for storage by increasing trade. Smart contracts could also be used to manage balancing activities and virtual power plants, both relevant for a power system with very high shares of variable renewable energy.

Assuming blockchains are able to scale up the number of transactions processed while remaining fast and secure, they could help reduce the complexity of network operation. For example, a distribution system operator (DSO) or transmission service operator (TSO) could operate a (private) permissioned blockchain; all devices connected to the DSO or TSO electricity grid would also be connected to its blockchain, enabling the tracking of transactions. This would support the DSO or TSO in not only supervising, but also intervening if necessary. For example, Elia, Belgium's TSO, is currently learning how to use blockchain technology initially to target certain processes in the area of demand response, in particular registration, measurement and verification, and financial settlement (EWF, 2018c). In addition, Electron is working with an industry consortium, including National Grid, EDF and Shell, to look at how grid-edge assets can be integrated into the grid to reduce costs and carbon emissions while increasing reliability. TenneT, a TSO in Germany, is using blockchain in a pilot project to procure balancing services from behind-the-meter batteries.

Financing renewable energy through hybrid asset classes

Despite a staggering number of people lacking access to energy globally, and hundreds of billions being invested in renewable energy annually by the public and private sectors, the roll-out of renewable energy is not moving quickly enough to address climate needs while improving access to modern energy services. An opening still appears to exist for financing mechanisms and marketplaces to bring together energy demand and finance supply. Blockchain technology offers an attractive platform for this through its potentially low transaction costs, efficient processing and security features provided by smart contracts, and its payment capabilities. Companies such as The Sun Exchange and ImpactPPA aim to accelerate the financing of renewable energy using the power of blockchain.

P2P ledgers have ushered in an era of new "crypto" assets that can be freely traded by the general public or used as tokens to purchase goods and services on a specific network. Since the digital assets change hands at the agreed value directly between the buyer and the seller, commissions are saved in the process. These blockchain-based assets are quite promising for the financing of renewable energy projects. Token crowd sales are being used as a way to raise capital for infrastructure, while the tokens themselves will later change hands just as money, with the difference being that this is money that may yield increased value over time, as shares in a company might. In a sense, tokens represent the gross domestic product (GDP) of a network: the more a network (Ethereum for example) is used, the more valuable the tokens become as their usefulness increases.

Management of renewable energy certificates

In many cases, renewable energy certificates (RECs) are awarded on the basis of estimates and forecasts rather than on actual generation. In the European Union, guarantee of origin (GO) legislation is in place that requires the issuing of GOs to be based on measurement of the electricity produced. These GOs can be traded within the European Union, and can be used to provide proof that the electricity consumed was indeed renewable. This legislation also stipulates that "...with a view to ensuring a unit of electricity from renewable energy sources is disclosed to a customer only once, double counting and double disclosure of guarantees of origin should be avoided..." (European Union, 2009). The potential role for blockchain is clear,

as double spending is prevented via cryptography and decentralised consensus.

With blockchain technology, distributed renewable energy producers (*e.g.* rooftop solar) can be awarded RECs in real time, as their power is generated. Sensors and smart contracts can record and propagate real-time generation data throughout the network. A central verification agency to verify generation data may no longer be needed as all data would be secured and viewable on the blockchain. With this new technology, public agencies administering RECs could reduce costs by streamlining data verification and automating REC awarding. Notably, however, that verification of meter readings is still an issue that requires exploration in a decentralised solution (McKinsey & Company, 2018).

Electric mobility

Blockchains might also play an important role in the development of electromobility, underpinning the platform that co-ordinates EV charging. EV owners would be able to stop at any charging station, including residential locations, that is registered on the blockchain and trade power for payment in real time, without any centralised intermediary required. Smart contracts would also allow for automatic and secure P2P payments. By providing the basis for a larger and more efficient charging network, blockchains could enable widespread adoption of not only e-mobility, but also the distributed renewable energy generation needed to power it.

Rural electrification and increased access to modern energy services

While not a main aim of the initiatives discussed above, progress in rural electrification may be achieved due to the burgeoning use of blockchain in the power sector. Nearly 1 billion people still live without reliable access to electricity – 500 million in Africa and more than 400 million in the Asia-Pacific region alone (IEA, IRENA, UN, WBG and WHO, 2018). By allowing local solar generators to sell power to their surrounding neighbours, blockchains can help facilitate the distribution of small amounts of energy in underserved areas when combined with smart and innovative financing schemes, mobile applications and digital sensors.

This approach can work as follows. The prospective generator installs a blockchain-enabled solar panel on credit from the installer, using a mobile phone to pay for the hardware in instalments and incurring minimal fees. Once the solar installation is paid for, the owner can sell excess solar power to nearby consumers as needed. Power requests and payments can be made seamlessly via mobile phone. The lighter fixed infrastructure involved with blockchains and mobile micropayments allows these networks to thrive where other infrastructure – wires, traditional loan structures and centralised energy authorities, for example – might be too cumbersome (McKinsey & Company, 2018).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Maturing technology: Improving performance and scalability

Blockchain networks need to scale up to enable the widespread adoption of the technology in the power sector and in other sectors. This includes: increasing the number of transactions per second (TPS) processed in these networks; reducing block time (how often computations on the blockchain are bundled and verified); and increasing the block size limit (the amount of transactions bundled in each block).

Early protocols, including Bitcoin and Ethereum, boasted throughputs of about 10 TPS and 30 TPS, respectively. VisaNet, the centralised processing service for the international Visa network, can handle more than 65 000 TPS (Visa, 2018). Mass adoption in the power sector and others would require thousands of TPS, particularly as the number of internet-connected devices continues to increase. There exists a trade-off, however: the more decentralised a network is (*i.e.* the larger the number of individual nodes processing transactions), the harder it is to maintain a higher number of TPS. If decentralisation is not an important consideration for a particular use case, blockchain is most likely not the appropriate tool to process transactions. The pros and cons of decentralisation and speed are widely discussed in various fora today.

A promising means of tackling scaling is the use of parallel interoperable chains, or "sidechains". This approach essentially delegates some computational responsibility to subordinate chains, which report and notarise their results to other chains. The network thus achieves consensus by parallel processing computations, rather than burdening a single chain.

Consider a hypothetical example for the German energy market. Rather than a single blockchain for all of Germany, there could be one main chain for Germany, but then also separate chains for each of its 16 federal states, and 20 more chains for each larger city in each of the states. The result would be 337 chains stacked on three layers, increasing throughput by three orders of magnitude compared to a single chain. This architecture would also address data sovereignty regulations, which require data to be stored within specific geographical boundaries (EWF, 2018d).

Another potential way to manage the speed and scale issues associated with an open platform that uses proof of work for consensus is to employ an alternative consensus algorithm, such as proof of stake or proof of authority.[8] In addition, certain data can be stored off blockchain or frozen, thereby allowing enhanced processing times. Importantly, blockchain technology is still developing, and

8 Proof of authority (PoA) is a replacement for proof of work, which can be used for private chain setups. It does not depend on nodes solving arbitrarily difficult mathematical problems, but instead uses a set of "authorities" – nodes that are explicitly allowed to create new blocks and secure the blockchain. Hashgraph, a leading example of a network using PoA for consensus, uses a governance model where a council, consisting of 39 public organisations in a variety of fields serving 3-year terms, make decisions for the platform as a whole. These 39 organisations act as network authorities.

performance and scalability will continue to improve with time. To nurture this development, more developers will be needed. The current shortage of developers required to code the decentralised applications, and the blockchains on which they run, has led to high development costs – a substantial hurdle.

Establishing clear and consistent regulations

The regulatory environment for blockchain remains uncertain. A lack of blockchain procedures or global regulation also means that the procedure for handling disputes, wrongdoings and transaction reversals is inconsistent and legally uncertain. Due to the nature of blockchains and the generation of coins or tokens to incentivise the validation of transactions (*i.e.* mining), a new asset class has emerged to reflect the inherent value of these coins. Because of the substantial funds being invested in this growing asset class, blockchain technology as a whole is facing increased scrutiny, and governments are grappling with how to adapt regulation and taxation. Markets with less regulatory uncertainty are seeing a boom in blockchain-related start-ups and overall adoption.

In March 2017, ELECTRIFY, Singapore's first retail electricity marketplace, raised over USD 30 million from investors to build their platform. ELECTRIFY's Marketplace 2.0 system will allow consumers to browse and purchase electricity from a variety of providers starting in the second half of 2018, while smart contracts will connect to digital wallets that facilitate bill payment and platform services fees (Electrify.Asia, 2017). Grid+ in the United States, WePower in Europe and PowerLedger in Australia have raised similar amounts to build their respective platforms.

Due to the overarching uncertainty and the overall lack of awareness surrounding blockchain technology, most blockchain platforms in the power sector are currently being tested only for behind-the-meter applications as part of regulatory sandboxes established in certain countries to test these technologies. This requires minimal changes to the energy regulatory regime and provides consumers with more flexibility or independence. However, blockchain technology has the potential to transform larger interconnected grids for which the stakeholders will initially need established regulations and technical standards for operations. To achieve this, power sector regulatory environments should be clearly defined and stable, so that tools like blockchain can be developed and used for specific applications where value can be added. Frameworks that better enable and encourage decentralised transaction models would more effectively facilitate the use of blockchain technology. Clear and consistent regulations are needed to nurture this new decentralised internet. Policy makers and regulators need a clear understanding of blockchain use cases and capabilities before being able to properly address policy and regulatory needs.

Blockchain technology might hold the potential to simplify the process of regulation and increase efficiency through the use of data analytics. If regulators gain access to primary records and real-time information of all involved participants, they could then analyse and understand all the processes in which the participating entities are involved. Furthermore, blockchain could simplify the interaction between regulators and regulated entities. For example, increased transparency regarding DSO activities, via the blockchain, could change the way network operators manage their grids.

When it comes to standards, an important question remains: How can we ensure compatibility between different blockchain technologies, so that they can scale up and have an impact? Interoperability between different blockchain solutions remains an issue.

Reducing power consumption

Proof-of-work technologies, such as Bitcoin and Ethereum, rely on mining[9] to validate transactions and secure the network by solving complex cryptographic puzzles. In early 2018, each Bitcoin transaction required a vast amount of computing

9 Mining means securing the blockchain by validating transactions and adding new blocks to the chain through the solving of complex mathematic puzzles, which is very power intensive. As more computing power is added to the network, the average number of calculations required to create a new block increases, thus increasing validation difficulty.

power, and thus electricity. Each transaction required approximately 300 kWh, meaning the Bitcoin network as a whole required a continuous 3.4 gigawatts (GW) or 30 terawatt hours (TWh) per year, more than the entire country of Austria (Krause and Tolaymat, 2018; Digiconomist, 2018a).

For blockchain technology to sustainably transform the power sector, along with countless others, a shift from proof of work to other means of transaction validation and network consensus achievement, such as proof of stake,[10] proof of authority, or web 3.0 technologies such as non-linear "tangles",[11] will be required. Ethereum is currently in the process of shifting to a proof-of-stake validation model to dramatically increase transactions per second while drastically reducing power requirements; it is seeking to complete this transition by 2019 or 2020. Notably, many power sector applications of blockchain currently use less energy-intensive protocols that do not rely on proof of work.

Enhancing grid infrastructure

Blockchain technology is extremely versatile and is replicable in any geography with a grid of substantial size. To optimise the use blockchain technology for renewable energy, it is crucial to move towards a more interconnected, technology-enabled smart grid. Currently, many companies are forced to make their own smart meters because they cannot access the data of legacy companies. Grid-interactive infrastructure is needed to take advantage of the benefits that DLTs such as blockchain provide. However, it may take some time and sustained effort to install smart digital meters and other devices to facilitate interconnectivity and increase the amount of transactions processed via blockchain technologies. Additionally, with respect to building out infrastructure, people are still needed to maintain poles and wires and to build new physical grids in remote locations.

Better understanding of the technology applications and developing user-friendly solutions

As blockchain technology matures, it becomes more versatile and the number of uses grows. Despite the numerous potential benefits of blockchain solutions in the power sector for retail users (frictionless P2P trade and payments, instant collection of RECs, among others), new applications with user-friendly interfaces are needed. To provide a straightforward, consistent and positive experience, applications need to be developed for use by individual consumers and small-scale renewable energy generators. For that, a better understanding of this technology and its applicability in all dimensions of the power sector is needed. Current electricity trading platforms are geared towards large-scale brokers and are not intuitive or accessible to the general public.

The ability to easily purchase a small share of a nearby solar farm on your mobile phone and collect revenues based on the power generated, or use it for your own residential consumption (all tracked in real time on your mobile device), will open up access to renewable electricity to a swathe of new consumers. A more transparent and user-friendly solution will also help catalyse small-scale investments in blockchain technologies worldwide, spurring even more innovation in this new field (EWF, 2018d).

10 Unlike the proof-of-work system, in which the user validates transactions and creates new blocks by performing a certain amount of computational work, a proof-of-stake system requires the user to show ownership of a certain number of cryptocurrency units. The creator of a new block is chosen in a pseudo-random way, depending on the amount of coins a user holds.

11 Also known as directed acyclic graph (DAG) technologies. A directed graph data structure uses a topological ordering. The sequence can only go from earlier to later. DAG is often applied to problems related to data processing, scheduling, finding the best route in navigation, and data compression.

IV. CURRENT STATUS AND EXAMPLES OF LEADING INITIATIVES

Recently, Blockchain2business and SolarPlaza analysed over 150 leading companies and pilot projects working with blockchain and energy. The following are some of the key insights (B2B, 2018):

- **Over 46 %** of these blockchain energy start-ups are concentrated **in Europe**.
- The **top 3** countries are the **United States, Germany** and the **Netherlands**.
- The most common use is **P2P energy trading**.
- Around **50 %** of the projects use the **Ethereum** blockchain.
- Close to **74 %** of the companies were started/ founded between **2016** and **2018**, which reflects the early stage of the technology.

Power consumption:

- In early 2018, each **Bitcoin transaction** required approximately **300 kWh**, enough to power over 8 US households for a full day. The Bitcoin network as a whole required a continuous **3.4 GW** or **30 TWh** per year, more than **Austria's** annual electricity consumption (Krause and Tolaymat, 2018; Digiconomist, 2018a; Digiconomist, 2018b).
- **The two largest blockchain**s (Bitcoin and Ethereum) combined consume **42.67 TWh** annually, **0.19 %** of the **world's electricity** (Digiconomist, 2018a; Digiconomist, 2018b).
- New means of reaching consensus, such as **proof of stake** and **proof of authority**, will help to greatly reduce power consumption as they are adopted.

A separate study by GTM Research/Wood Mackenzie Power and Renewables assessed the scale of current blockchain activity in the power sector (Table 1).

Currently, start-ups and consortiums focused on the power sector are largely choosing to build their second-layer applications on the Ethereum platform, due to its size (large number of nodes which work to validate transactions), ability to host smart contracts, stability, and plans for increased scalability and speed with a shift in the consensus model to proof of stake. A variety of uses for blockchain are being studied in the power sector at the moment, but the main areas of focus revolve around the optimisation of grid management processes and P2P, peer-to-business (P2B) and business-to-business (B2B) wholesale electricity trading without intermediation.

On 10 April 2018, 22 European countries[12] signed a declaration on the establishment of a European Blockchain Partnership. It is designed to act as a vehicle for co-operation among EU member states to exchange experience and expertise in preparation for the launch of EU-wide blockchain applications across the Digital Single Market. The aim is to ensure that Europe continues to play a

12 *Since the initial signing of the declaration on 10 April 2018, 5 more EU member states have joined the partnership, bringing the total number of signatories to 27.*

Table 1 Extent of blockchain activity in the power sector

Description	Value
Number of companies working in blockchain in the power sector	189
Number of companies leading blockchain projects in Grid Edge space	32
Amount invested in blockchain power companies	USD 466 million, 79 % of which came from Initial Coin Offerings
Amount raised by start-up companies in 2017 to apply blockchain technology to power sector	USD 300 million
Number of projects happening globally	71 announced

Note: Data valid as of 31 July 2018.
Source: Metelitsa (2018), "A snapshot into blockchain deployments and investments in the power sector".

leading role in the development and roll-out of blockchain technologies, including for use in the power sector (European Commission, 2018).

In early March 2018 the International Energy Research Centre and others launched EnerPort, a new project which aims to accelerate P2P electricity trading in Ireland through blockchain. Some of the challenges to be addressed include: trust and validation of transactions made in distributed energy networks; how to foster stronger consumer engagement within that market; and how to free up the trading regulations within local networks as technologies such as electricity storage systems, EVs and smart home devices are deployed (IERC, 2018).

The following tables present a non-exhaustive sample of companies, consortiums, foundations and groups working at the intersection of blockchain and energy, particularly renewable power. When blockchain technology and the world of energy intersect, several application categories emerge. Among these categories are: P2P transactions, grid management and system operation, financing renewable energy development, management of RECs and certification of origin, and electric mobility. For each of these categories, a series of companies, consortiums, foundations and working groups will be mentioned, indicating its name, country of origin, as well as a brief description of it.

Table 2 Example of initiatives that use blockchain for peer to peer electricity trading

Actor	Business	Country	Brief description
Conjoule	Private company	Germany	Conjoule offers a blockchain platform designed to support P2P trading of energy among rooftop photovoltaic (PV) owners and interested public-sector or corporate buyers.
Electrify.Asia	Private company	Singapore	Electrify.Asia is developing a marketplace which acts as a web and mobile platform allowing consumers to purchase energy from electricity retailers or directly from their peers (P2P) with smart contracts and blockchain.
Electron	Private company	United Kingdom	Electron began with a blockchain-based solution to help customers in the United Kingdom switch energy suppliers, but has since been communicating a vision of leveraging its platform to support broader energy trading and grid-balancing solutions.
Greeneum	Private company	Israel	Greeneum is running test nets and pilots for its P2P energy trading platform in Europe, Cyprus, Israel, Africa and the United States. It expects to have a viable product platform out by mid-2018.
LO3 Energy	Private company	United States	Backed by Siemens, P2P blockchain developer LO3 Energy operates the Brooklyn Microgrid, which augments the traditional energy grid, letting participants tap into community resources to generate, store, buy and sell energy at the local level. This model makes clean, renewable energy more accessible, and keeps the community resilient to outages in emergencies, among many other economic and environmental benefits.
Power Ledger	Private company	Australia	The Power Ledger platform forms P2P energy transactions by recording both the generation and consumption of all platform participants in real time. The company is rolling out pilot projects for its blockchain platform, built to support a broad range of energy market applications, in Australia and New Zealand.
Sonnen	Private company	Germany	Redispatch measures prevent regional overloads on the grid. In this pilot project with sonnen eServices, a network of residential solar batteries will be made available to help address the limitations associated with wind energy transmission capacity. Blockchain technology provides the operator from TenneT with a view of the available pool of flexibility, ready to activate at the push of a button, after which the blockchain records batteries' contribution.
Axpo	Utility	Switzerland	Axpo launched a P2P platform that allows consumers to buy electricity directly from renewable producers.
Vattenfall	Utility	Sweden	Vattenfall is piloting Powerpeers, a marketplace for P2P energy trading; it has joined the Enerchain framework.
National Renewable Energy Laboratory	Government-level regulatory initiatives	United States	NREL is partnering with Blockcypher to demonstrate transactions of distributed energy resources across multiple blockchains.
National Grid UK	Utility	United Kingdom	National Grid is backing the energy trading platform launched by Electron.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 3 Examples of initiatives that use blockchain for grid management and system operation

Actor	Business	Country	Brief description
Energy Web Foundation	Non-profit organisation	Switzerland	Established in February 2017 by Grid Singularity and the Rocky Mountain Institute, Energy Web Foundation (EWF) is a global non-profit organisation focused on accelerating blockchain technology across the energy sector and is developing a new open-source, energy-focused blockchain platform that provides the functionalities needed to implement energy sector use cases at scale.
Ponton	Private company	Germany	Operates Enerchain, a blockchain-powered wholesale electricity trading platform.
Sunchain	Private company	France	Distributed solar power storage for private prosumers.
Eneco	Utility	Netherlands	Piloting a blockchain application to create a decentralised heating network in Rotterdam.
Enel	Utility	Italy	Joined Enerchain framework to conduct P2P trading in the wholesale energy market.
E.ON	Utility	Germany	Joined Enerchain framework to conduct direct electricity trading between energy companies.
Iberdrola	Utility	Spain	Joined Enerchain framework to conduct direct electricity trading between energy companies.
German Ministry of Economic Affairs and Energy	Government-level regulatory initiatives	Germany	Piloting a large-scale decentralised and integrated platform for renewable generation, transmission and distribution infrastructure.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide sto Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 4 Examples of initiatives that use blockchain for management of renewable certificates and certification of origin

Actor	Business	Country	Brief description
CarbonX	Private company	Canada	P2P carbon credit trading platform.
ElectriCChain	Private company	Andorra	Market platform for auditing decentralised solar power generation data.
Energy Blockchain Labs	Private company	China	Platform for trading decentralised carbon assets.
SolarCoin	Private company	United States	SolarCoin was launched in 2014 as a rewards programme for solar electricity generation, with one of its coins equalling a megawatt hour of production. The scheme is set to reward 97 500 TWh of generation over 40 years, but for now its value remains low.
Veridium	Private company	United States	Veridium is a financial technology firm aiming to create a new asset class called "EcoSmart Commodities". Veridium will provide a new vehicle for corporations to embed environmental replacements into the cost of their products.
Volt Markets	Private company	United States	Platform that issues, tracks and trades RECs.
Engie	Private company	France	Working with Air Products to certify renewable energy use in production processes.
SP Group	Utility	Singapore	Launched blockchain-enabled platform to transact RECs.
Russia Carbon Fund	Utility	Russian Federation	Developing an audit system for climate projects with E&Y.
Sustainable Energy Development Authority	Government-level regulatory initiatives	Malaysia	Invested in P2P a marketplace project run by Power Ledger.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 5 Examples of initiatives that use blockchain for financing renewable energy deployment

Actor	Business	Country	Brief description
ImpactPPA	Private company	United States	While most energy-based blockchain players offer a token for trading, California-based ImpactPPA has two: one to fund projects and one to consume energy. The company is targeting the estimated 16 % of the world population that lacks a reliable source of energy.
M-PayG	Private company	Denmark	Pay-as-you-go solar energy for households across the developing world.
MyBit	Private company	Switzerland	MyBit is designed to help crowdfund solar panels by distributing the ownership of each system across several owners. The company raised the equivalent of around USD 2.7 million in a token sale in August.
The Sun Exchange	Private company	South Africa	The Sun Exchange aims to let supporters around the world crowdfund PV down to the level of an individual solar cell and lease them to schools and businesses in Africa. The company's marketplace is focused on funding and building new generation systems, rather than trading power. Sun Exchange has been operational for several years and has successfully funded four solar projects.
WePower	Private company	Lithuania	WePower is developing an Ethereum-based platform to fund renewable energy projects through the sale and trading of the "tokenised" energy produced by those systems. The company raised USD 40 million in funding in 2017.
Direct Energy	Utility	United States	Partnered with LO3 Energy to offer "micro-energy hedging" in energy markets.
Endesa	Utility	Spain	Joined Enerchain framework to conduct direct electricity trading between energy companies.
Enercity	Utility	Germany	Accepts bitcoin for bill payments.
Ministry of Micro, Small and Medium Enterprises	Government-level regulatory initiatives	India	Using Ethereum blockchain to manage supply chain logistics for renewable energy-powered textile looms.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

Table 6 Examples of initatives that use blockchain for electric mobility

Actor	Business	Country	Brief description
eMotor Werks	Private company	United States	P2P EV charging network through partnership with Share&Charge platform.
MotionWerk	Private company	Germany	Partnership with Slock.it on Share&Charge platform, which provides decentralised EV charging locations.
Slock.it	Private company	Germany	Partnership with MotionWerk to develop Share&Charge platform.
Chubu Electric Power Company	Utility	Japan	Piloting blockchain-based EV charging service.
Enexis	Utility	Netherlands	Prototyping IOTA-enabled cryptocurrency transactions for EV charging.
Pacific Gas and Electricity (PG&E)	Utility	United States	Has approved eMotor Werks and Oxygen Initiative as vendors for its 7 500 EV charging station expansion plan.
TenneT	Utility	Germany	Developing blockchain-based system that integrates household batteries and charging for EVs.

Table data sourced from: GTM (2018), "15 firms leading the way on energy blockchain", www.greentechmedia.com/articles/read/leading-energy-blockchain-firms; SolarPlaza (2018), Comprehensive Guide to Companies involved in Blockchain & Energy; Livingston et al. (2018), Applying Blockchain Technology to Electric Power Systems; as well as individual websites.

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Smart grid, smart metering • Smart phones or computers
	Software: • Blockchain support software • Smart contracts and cloud platforms
	Communication protocols: • Scale protocols to handle increased transaction loads while maintaining security and increasing speeds • Common interoperable standards along with data storage and identity, smart contracts
POLICIES NEEDED	**Strategic policies could include:** • Regulation and supervisory role for promoting safe, efficient and cost-effective electricity transmission and exchange • Regulation for the interaction of new blockchain-based trading and evolution of existing electricity trading regulations • Promotion of decentralised generation
REGULATORY REQUIREMENTS	Market regulations that enable electricity exchange between consumers and prosumers (for P2P trading applications), and between prosumers and system operators (for grid transactions) **Retail market:** • Customer and producer support and empowerment • Understanding of the need for open market dynamics • Certainty in the ability of prosumers to freely sell power generated from residential distributed energy resources to other grid-connected consumers
	Distribution: • Incentivise DSOs to modify their business models and take up the role of a facilitator and supervisor • Organise payment rules for use of the DSO electricity grid and potentially also the use of the TSO grid if exchange over multiple DSOs is needed
STAKEHOLDER ROLES AND RESPONSIBILITIES	**Electricity market participants:** • Existing roles in the power sector might shift substantially: retailers may face reduced need if all data (and electricity) is exchanged directly between the electricity producer and the consumer, for example • Organise rules to balance consumption and production, and determine consequences if balance is not achieved; • Empower consumers through P2P trading and transparent, decentralised information sharing

ACRONYMS AND ABBREVIATIONS

B2B	business-to-business
DAG	directed acyclic graph
DLT	distributed ledger technology
DSO	distribution system operator
GO	guarantee of origin
EV	electric vehicle
P2B	peer-to-business
P2P	peer-to-peer
PoA	proof of authority
PoS	proof of stake
PoW	proof of work
PV	photovoltaic
REC	renewable energy certificate
TSO	transmission system operator

UNITS OF MEASUREMENT

GW	gigawatt
kWh	kilowatt hour
TPS	transactions per second
TWh	terawatt hour

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