European Commission

JRC SCIENCE FOR POLICY REPORT

Blockchain solutions for the energy transition

Experimental evidence and policy recommendations

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2022

Joint Research Centre

EUR 31008 EN

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JRC128651

EUR 31008 EN

PDF ISBN 978-92-76-49089-0 ISSN 1831-9424 doi:10.2760/62246

Luxembourg: Publications Office of the European Union, 2022

How to cite this report: Fulli G., Nai Fovino I. Andreadou N., Geneiatakis D., Giuliani R., Joanny G., Kotsakis V., Kounelis I., Lucas A., Martin T., O'Neill G., Sachy M., Soupionis Y., Steri G., *Blockchain solutions for the energy transition: experimental evidence and policy recommendations*, EUR 31008 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-49089-0, doi:10.2760/62246, JRC128651.

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ACKNOWLEDGEMENTS

We would like to thank our DG ENER colleagues, Manuel Sanchez Jimenez and Constantina Filiou, for inviting us to undertake this interesting and challenging project.

We also wish to thank our EC colleagues Charles Cleret de Langavant (ENER), Lukas Repa (CNECT), Enrique Aresti Gutierrez and Luis Miguel Vega Fidalgo (GROW), Helena Hernnas (ECFIN), Alexandru Ciungu (ECFIN) and Asa Linden Ohannesson (ECFIN) for their comments and feedback provided at different stages of drafting of this document.

Our gratitude goes also to Marcelo Masera and Jean-Pierre Nordvik (JRC) for their continuous support throughout the whole project execution.

Finally, thanks to other JRC colleagues Carine Nieuweling, Dimitrios Thomas and Anna Mengolini for their assistance, comments and insights, and Massimiliano Gusmini for his graphic design support.

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ABSTRACT

This report summarises the main outcomes of several experimental studies carried out by the Joint Research Centre on blockchain solutions for energy systems. It presents considerations and recommendations for European policymakers regarding blockchain deployment across the energy value chain.

The outcomes of this report come from a multi-year project funded through an explicit request of the European Parliament to the European Commission, with experiments conducted in the Joint Research Centre smart grids and cybersecurity laboratories.

EXECUTIVE SUMMARY

Europe's future will be strongly influenced by the successful achievement of the twin digital and green transitions. The Covid-19 pandemic crisis has clearly magnified the role that digital and energy technologies have on people, businesses and the economy. We saw how heavily we rely on digital and energy solutions to enable us to telework, heat our homes, manage our hospitals, and run our businesses. Monitoring the evolution of digital technologies to identify the most promising and disruptive ones is of primary importance in the effort to support and speed up the race of the European Union towards a greener and more sustainable future.

An emerging technology to support the twin digital and green transitions

Among the many digital technologies in use and in development, **blockchain technologies**[1] are proving that they have a lot to offer in supporting and streamlining evidence-based decision-making in the fields of climate and sustainable energy. Blockchain can be imagined as an electronic register distributed over a myriad of computers and nodes, where each node can update and store a copy of the register.

Some reasons why blockchain is appealing for applications in the climate and energy sectors are:

- Disintermediation: Currently most of the worlds' financial, energy and other operations are enabled by intermediaries such as banks and market operators. Blockchain removes the need for such trusted third parties to oversee and validate information/value exchanges.
- Transparency and verifiability: transactions recorded on a blockchain are able to be checked independently. Illicit transactions are detected and excluded from the blockchain, rendering it impossible for the parties involved to perform malicious operations.
- Immutability and security: it is almost impossible to modify or tamper with information recorded on a blockchain (even when many nodes are attacked at the same time).

State-of-play of blockchain in the energy sector

In 2018, the European Parliament requested the Commission to investigate the impact of blockchain on the energy sector. The Joint Research Centre (the European Commission's science and knowledge service) consequently conducted a desktop and experimental project analysis of how blockchain can enable, and potentially revolutionise, the energy market and system operations.

The study found that:

- there is a **clear interest among energy and digital industries to exploit the potential of blockchain**. Pilots and use-cases are already flourishing all around Europe. In-house tests on technological performances and scalability confirmed the potential for these industries to use blockchain. However, **consumers** are **not yet fully engaged in digital energy projects** and independent aggregators **still face entry barriers** to participate in electricity markets.
- **The sustainability and the energy footprint of blockchain** is a heavily debated, but not always well-analysed, issue.
- Blockchain applications for **higher-level energy system functionalities** (i.e. applications running on layers not dealing with physical power grid operations) **are more numerous and mature**.
- Blockchain applications linked to **energy system operations** (i.e. directly impacting physical power grids operations, such as power dispatching) **are instead less developed**.

NOTES

[1] Throughout this report, we use the sub-set term 'blockchain' instead of the more comprehensive term 'Distributed Ledger Technology', DLT. A blockchain is a chain of data blocks serially interconnected one after the other, whereas DLT includes other data architectures beyond the chain of blocks, such as graphs and other solutions. We use this simplification because most of the DLT applications, also in the energy sector, are based on blockchain.

This is mainly due to lack of adequate guarantees in terms of safety, certification, and standardisation.

- Blockchain shows **high potential for use as the distributed driving brain of an energy community**. Blockchain appears suited to support the financial settlement of energy transactions, energy trading in local or wider markets, energy management and flexibility services provisioning, and several certification and billing processes.
- Adequate and interoperable **smart metering infrastructure is indispensable for the activation of blockchain services** for energy communities and peer-to-peer energy trading.

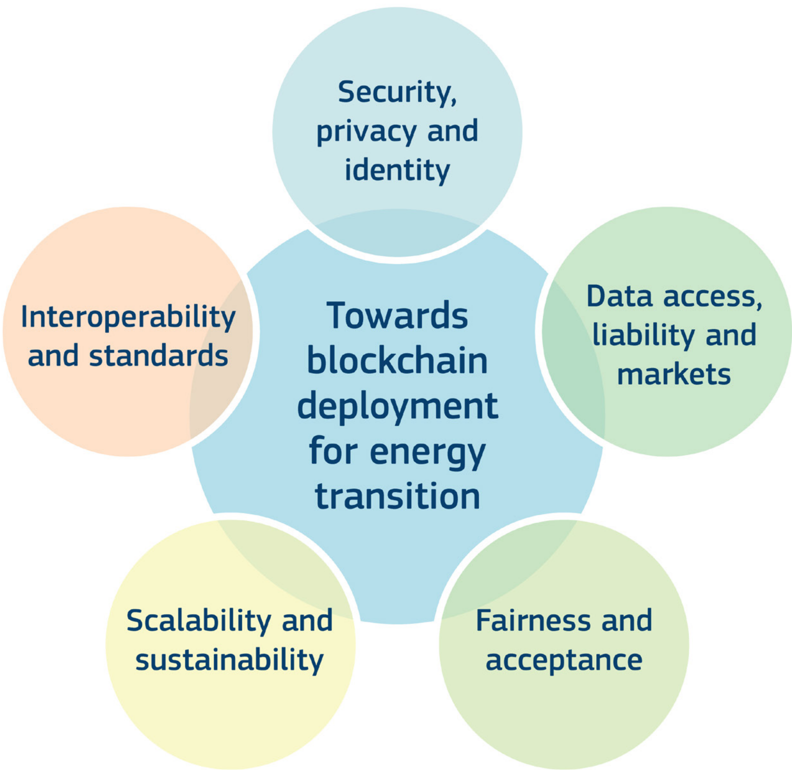
Recommendations presented by cluster

During the study, it became clear that several aspects and interfaces must still be clarified to successfully govern the introduction of blockchain-based electricity delivery options and services. To this end, drawing upon the desktop and experimental research conducted, the following clusters of recommendations to address emerging trends and issues were identified:

Security, privacy & identity

- Requirements to ensure that blockchain applications maintain adequate cybersecurity and electricity supply security levels should be defined.
- Mechanisms to safeguard data security and integrity should be further developed.
- Data should be protected 'by design' and shared only as needed to activate consented blockchain-enabled services.
- Effective integration strategies between data protection and cybersecurity initiatives are needed.
- The resilience and security of modern telecommunication networks and the Internet should be assessed, from a cybersecurity perspective, for the impact of energy digitalisation.
- Cybersecurity certification schemes should increasingly cover both the domain of blockchain core infrastructure and the domain of end user applications and devices (e.g. Internet of Things).
- Strong authentication schemes should be embedded in the design of blockchain solutions.

Recommendations by cluster towards blockchain deployment for energy transition
Source: EC



Data access, liability and markets

- Robust energy data hubs/platforms, with agreed rules for data access and use, should be designed.
- Market rules should be adapted to take into account the emergence of new 'automated agent' actors.
- Decentralised responsibilities of electricity supply and delivery should be clearly defined and allocated.

Fairness and acceptance

- Fairness should be a guiding principle for designing more decentralised energy markets not discriminating any player, be they people or businesses.
- Consumers should be further involved and incentivised to invest in blockchain projects.
- A balance should be found between consumer empowerment and protection.

Scalability and sustainability

- The EU and national legislators should keep developing a comprehensive pro-innovation legal framework for digital applications.
- Regulatory experimentations should be further adopted.
- Analyses on the energy footprint of the blockchain solutions under testing/deployment should always accompany the studies on the scalability and performance requirements.

Interoperability and standards

- The EU and Member States stakeholders should continue their involvement in the work of international standard organisations.
- Proper standards and interoperability of blockchain-enabled devices (including meters, sensors, and appliances) should be promoted.

Next steps for the EU to exploit blockchain for energy

The EU and national legislators are encouraged to keep developing a comprehensive pro-innovation legal framework for digital applications, also better regulating blockchain-enabled digital assets and smart contracts.

The EC Digitalisation of Energy Action Plan represents a powerful toolbox to implement actions for a wider deployment of digital technologies, including blockchain, in the energy sector.

While the Digital Transformation is a key enabler to reach the Green Deal objectives, a consistent approach in the regulation of several cross-cutting sectors (energy, transport, finance etc.) is equally needed.

It remains to be seen to what extent blockchain can support or subvert business models in the transitioning electricity systems and markets. Indeed, blockchain represents only one of the enabling technologies of power system innovation, to be combined with other digital technologies, such as including Artificial Intelligence, big data, and Internet of Things, to achieve the climate-neutrality and sustainability targets.

The Joint Research Centre smart grids and cybersecurity laboratories stand ready to scale-up their research activities in support of policy decision making and identifying critical issues in the deployment of blockchain and other emerging digital and energy technologies.

> *Blockchain technology can enable, and potentially* ***revolutionise****, the energy market*

1. INTRODUCTION

Europe's future will be strongly influenced by the successful achievement of the twin digital and green transitions. Identifying and embracing potential new technologies can help every European citizen to benefit from digital opportunities. In addition, these transitions will increase the EU's resilience by reducing dependency on third countries, influence the EU's global positioning on the global stage, and help the EU to reach targeted sustainability goals.

Blockchain (a subset of distributed ledger technologies, see also footnote 1 in the Executive Summary) has been identified as being potentially disruptive but highly relevant for boosting the digitalisation of European society. On one hand, they could herald a new era of digital services, but, on the other hand, their robustness, security, scalability and sustainability are not yet assured.

Blockchain technology allows entities such as people and organisations, but also machines and software, to establish secure operational agreements and transactions. The possibility of eliminating the use of intermediaries between producers and consumers has the potential to revolutionise how digital services are built and delivered.

In 2018, the Industry, Research and Energy Committee (ITRE) of the European Parliament tasked the European Commission to conduct a study on the potential advantages and disadvantages related to the use of blockchain technologies in the energy field.

The Joint Research Centre, the European Commission's science and knowledge service, conducted the study which included the deployment of blockchain-based energy distribution test-beds and use-cases. The results not only confirmed the enormous potential of this technology for the energy sector, but also magnified the need for blockchain platforms to be governed by more mature and standardised approaches. This would enhance safety, scalability and security aspects, which are key factors when dealing with critical infrastructures.

This report is a summary of the in-depth two year study. It does not present the details of the scientific experiments and results obtained, for which the related technical reports [1][2][3][24] can be consulted. Instead, it offers a high-level view of the possible use of blockchain technologies in the energy sector, reflecting on potential advantages and policy needs.

2. WHAT IS ENERGY DIGITALISATION AND WHY IS IT IMPORTANT?

Digital transformation is key to reach the EU's climate-neutrality targets and is already impacting the energy system design and operation. The European Union recently embraced ambitious overarching political initiatives in the green and digital fields, which have strong synergies:

- The European Green Deal is the EU's plan for sustainable growth. It aims to contribute to achieving the Paris Agreement objective of keeping the global temperature increase to below 2°C [4] compared to pre-industrial levels.
- The EU Digital Strategy addresses crucial digitalisation issues relating to privacy, security, safety and ethical standards and promotes the deployment of an infrastructure fit for the future [5].

These ambitions plans include new acts to reinforce/complement digital energy-relevant legislative actions – such as the Energy Union/ Clean Energy Package, the General Data Protection regulation, the Directive on security of network and information systems, and most recently the Digitalisation of Energy Action Plan (see also Figure 1) [4][5][22].

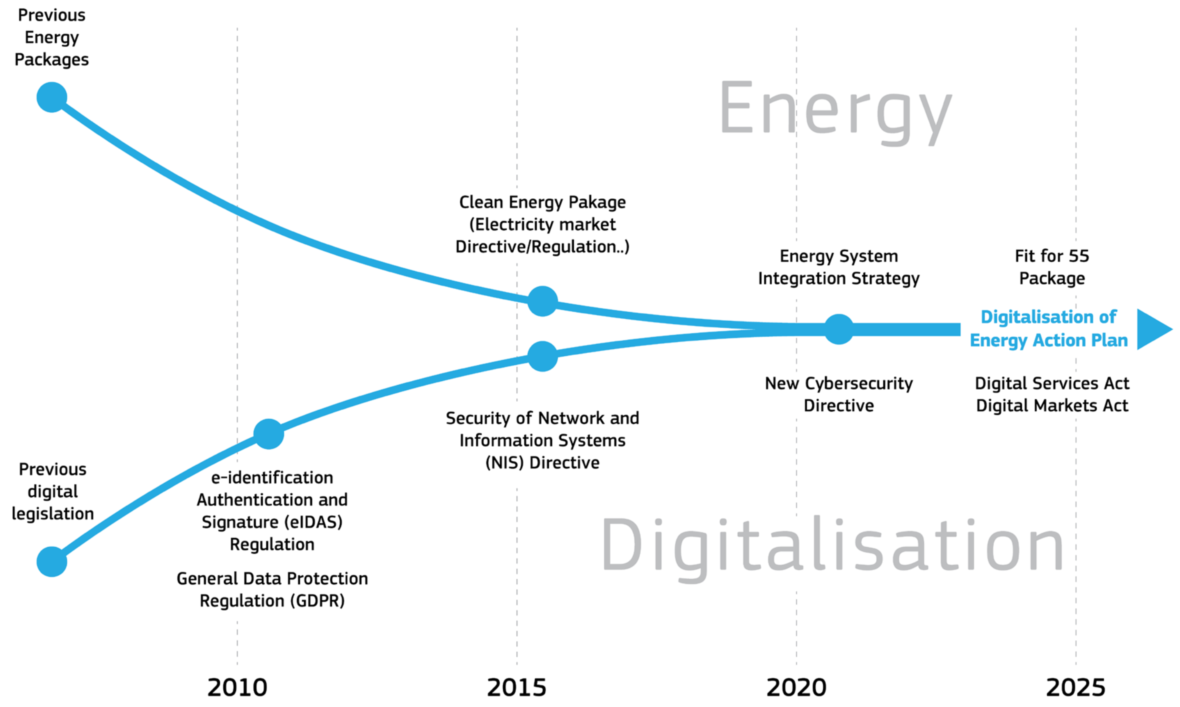
Digitalisation in the energy sector includes the creation and use of computerised information and processing of huge amounts of data, which is generated at all stages of the energy supply chain. There are great expectations for every segment of the energy ecosystem: households, prosumers, distribution, transmission, generation and retail, and is often stated as likely to lead to an energy system transformation.

Digitalisation offers the potential to increase energy efficiency through technologies that

FIGURE 1

Recent EU legislative initiatives on energy digitalisation [6]

Source: EC



gather and analyse data before using it to make changes to the physical environment (either automatically, or through human intervention). It is frequently linked with 'smart' energy, the Internet of Things (IoT) and Blockchain technology. The main goal of digitalisation is to improve efficiency through enabling better, cheaper and faster monitoring, recovery and maintenance of the assets and components through 'smarter' grids. For instance, smart households will facilitate own solar energy production, the Internet of Things (IoT) will integrate smart appliances for savings, ancillary grid services, and smart charging of Electric Vehicles.

The speed of digitalisation in energy is increasing. Investment in digital technologies by energy companies has grown sharply over the last years. For instance, according to the International Energy Agency[16], global investment in digital electricity infrastructure and software has risen by over 20% annually since 2014, reaching USD 47 billion in 2016 (Figure 2). This digital investment in 2016 was almost 40% higher than investment in gas-fired power generation worldwide (USD 34 billion) and almost equal to total investment in India's electricity sector (USD 55 billion).

2.1 Impact of digitalisation on energy demand

The impact of digitalisation on transport, buildings and industry is an undeniable fact.

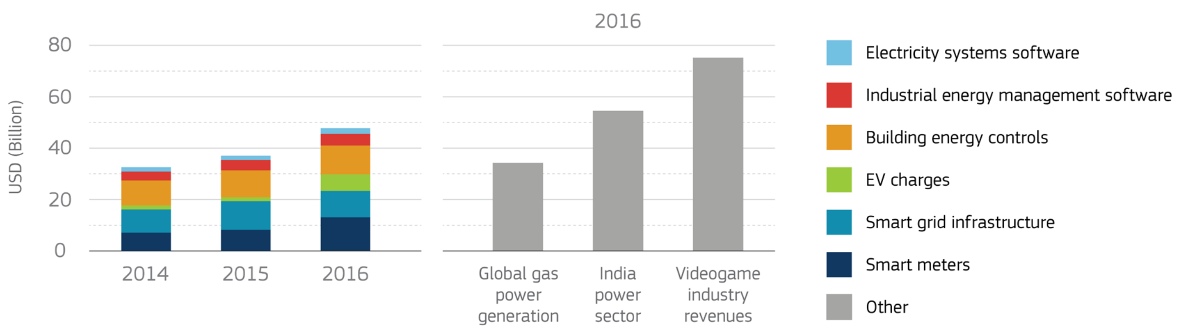
The availability of connectivity everywhere and the rise of artificial intelligence technologies are making the Transport sector smarter, with enormous advantages in relation to safety and efficiency. In road transport, connectivity is enabling new mobility sharing services. In combination with advancements in vehicle automation and electrification, digitalisation could result in considerable but uncertain energy and emissions impacts. In the long term, under a best-case scenario of improved efficiency through automation and ride-sharing, and with a positive interplay between technology, policy and behaviour, road transport energy use could potentially drop by about half [17]. Conversely, if efficiency improvements do not materialise and rebound effects from automation result in substantially more travel, energy use could more than double.

In buildings, digitalisation could decrease energy use by about 10% by using real-time

FIGURE 2

Investments in digital electricity infrastructure and software [16]

Source: EC



NOTES

[1] Digitalisation & Energy, International Energy Agency, 2018, https://www.iea.org/reports/digitalisation-and-energy

[2] Arbib, J. and Seba, T. (2017). Rethinking Transportation 2020-2030. www.rethinkx.com/transportation.

data to improve operational efficiency. Smart energy systems and thermostats can anticipate the behaviour of occupants (based on prior experience) and use real-time weather forecasts to better predict heating and cooling needs [18]. Smart lighting can deliver more than just light when and where it is needed; light-emitting diodes can also contain sensors linked to other systems – for example, helping to tailor heating and cooling services. However, it is important to be careful with digitalisation: the proliferation of new services and comforts (for example, the use of standby power by idle devices) could offset potential savings.

In industry, many companies have a long history of using digital technologies to improve safety and increase production. Further cost-effective energy savings can be realised through advanced process controls, and by coupling smart sensors and data analytics to predict equipment failure [20].

2.2 Impact of digitalisation on power supply

Energy companies have been using digital technologies for years, helping to increase the recovery of fossil resources, improve production processes, reduce costs and improve safety. An optimised use of digital technologies could decrease production costs between 10% and 20%, while recoverable oil and gas resources could be boosted by around 5% globally, with the greatest gains expected in shale gas [16].

In the coal industry, digital technologies are being used on a side in geological modelling, and on the other in more classical 'industrial processes' such as automation and predictive maintenance.

In the power sector, digitalisation has the potential to save around $80 billion per year, or about 5% of total annual power generation costs [16], based on the current system design and enhanced global deployment of available digital technologies to all power plants and network infrastructure. This can be attained by dropping operation and maintenance costs, improving power plant and network efficiency, reducing unplanned outages and downtime, and extending the operational lifetime of assets [19].

2.3 Impact of full digital interconnection of energy systems

The most important transformational prospective for digitalisation is its ability to break down the boundaries between energy sectors, increasing flexibility and enabling integration across entire systems. At the heart of this transformation is the electricity sector, where digitalisation makes the distinction between generation and consumption blurring, enabling a number of interrelated opportunities.

As reported by International Energy Agency (IEA) [16], smart demand response could provide 185GW of system flexibility, the equivalent of the combined electricity supply capacity of Australia and Italy. Still according to the IEA, “this could save $270 billion of investments in new electricity infrastructure”. The impact is potentially so huge that some studies [16] estimate the potential involvement of one billion households and 11 billion smart appliances in a new paradigm of interconnected electricity systems.

Digitalisation can facilitate the integration of intermitting renewables contributing to optimisation and synchronisation of energy demand with weather forecasts. In the European Union alone, increased storage and digitally enabled demand response could reduce curtailment of solar PV and wind power from 7% to 1.6% in 2040, avoiding 30 million tonnes of carbon dioxide emissions in 2040 [16].

Similarly, the same digital and AI technologies, if applied to the vehicle smart-charging domain could provide further flexibility to the grid while saving between $100 billion and $280 billion in avoided investment in new electricity infrastructure between 2016 and 2040 [16].

It is clear how, in this context, new tools such as blockchain could help to facilitate peer-to-peer electricity trade, but also aggregation and flexibility management.

3. BLOCKCHAIN TECHNOLOGIES, DIGITAL DECADE AND GREEN DEAL

In March 2021, the European Commission presented a vision and avenues for Europe's digital transformation by 2030 [25]. The Commission proposes a Digital Compass for the EU's digital decade that evolves around four cardinal points: infrastructures, business, government, skills. In this vision, blockchain technologies are mentioned among those technologies promising to boost and modernise European infrastructures. The EU recognises the potential of blockchain and supports the use of blockchain technology in fostering sustainable economic development, addressing climate change, and supporting the European Green New Deal.

The European Commission's strategy concerning blockchain technologies wants to support a 'gold standard' for blockchain technology in Europe that embraces European values and ideals in its legal and regulatory framework.

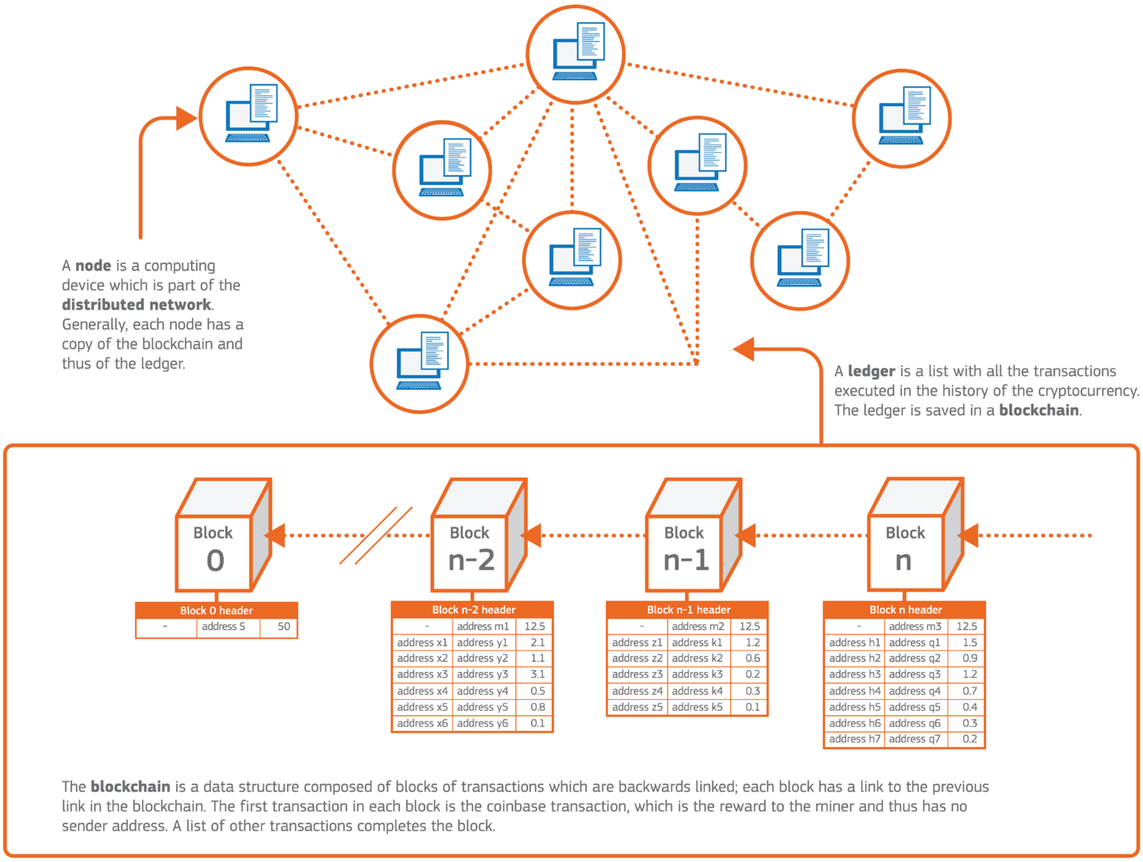
This 'gold standard' for blockchain includes:

- Environmental sustainability: Blockchain technology should be sustainable and energy-efficient.
- Data protection: Blockchain technology should be compatible with, and where possible support, Europe's strong data protection and privacy regulations.

FIGURE 3

An internal view of a blockchain structure in a cryptocurrency use case

Source: EC



- Digital Identity: Blockchain technology should respect and enhance Europe's evolving Digital Identity framework. This includes being compatible with e-signature regulations, such as electronic Identification, Authentication and Trust Services (eIDAS), and supporting a sensible, pragmatic decentralised and self-sovereign identity framework.
- Cybersecurity: Blockchain technology should be able to provide high levels of cybersecurity.
- Interoperability: Blockchains should be interoperable between themselves and with legacy systems in the outside world.

Application of blockchain technologies following these principles could pave the way to a digital revolution in many key sectors of the European economy and industry. However, it is important to underline that blockchains are not the solution for every problem, and a careful evaluation of use cases applications needs to be performed, to avoid wasting resources and security risks.

For this reason, before entering a discussion about the potential use of blockchain in the energy sector, it is important to recall the basic principles, and dispel recurrent myths and misunderstandings.

Blockchain technology allows people and organisations, who may not know or trust each other, to collectively agree on and permanently record information without a third-party authority. By creating trust in data in ways that were not possible before, blockchain has the potential to revolutionise how we share information and carry out transactions online.

Blockchain systems are specific data structures that record and synchronise data in chains of blocks with the support of cryptographic techniques enabling data consistency, integrity and immutability. Figure 3 illustrates an abstraction of a blockchain data structure.

End-user transactions are submitted to the network and transmitted to all the participants (nodes) over a peer-to-peer network. The transactions, once validated by a particular type of nodes, are stored in a block and distributed to all network entities. Each transaction is digitally signed[3] by the end-user's private cryptographic key[4] so no other entity can claim to be the transaction's originator.

In fact, all the participants in a blockchain network independently hold their own copy of the data, and can thus independently calculate the current known 'state' of the system. As a result, there is no single point of failure (as the ledger is stored in several nodes), in contrast to centralised data (storage) related services. Due to a synchronisation mechanism that the network supports in case of a participant's failure, the latest state of the system can be resumed. So, all the participants, at any time, share a common ground truth.

Another characteristic of the blockchain systems is the kind of access one has for reading, sending and validating transactions (see Figure 4). If anyone can read and access the blockchain, this is categorised as public, meaning that anyone can fetch the whole blockchain and read its contents. In contrast to the public blockchain, only authorised entities can have access a private blockchain. Similarly, depending on who can send and validate transactions, a blockchain is called permission-less or permissioned.

When making the decision to adopt a blockchain solution for a system, several parameters need to be taken into consideration. Depending on the developed system needs, different choices can be made. The most important characteristics that influence the choice are briefly discussed below.

Consensus Mechanisms and Energy Consumption

Probably the most important characteristic in a blockchain, the consensus mechanism is the way the system agrees on which transactions should be considered valid and added to the ledger. Consensus mechanisms are used to ensure honest behaviour by the parties involved. Bitcoin uses the Proof of Work (PoW),

NOTES

[3] A digital signature is a mathematical scheme for verifying the authenticity of digital messages or documents [8].

[4] Public-key cryptography is a cryptographic system that uses pairs of keys: public keys which may be disseminated widely, and private keys which are known only to the owner. Effective security only requires keeping the private key private; the public key can be openly distributed without compromising security [9].

which basically consists in assigning a difficult computational task to the network nodes to have the transaction proposed by a node stored on a block of the blockchain. Proof of work in Bitcoin is also the basis of the mining process.

Nowadays mining, especially in cryptocurrencies that are widely used, is increasingly considered as an unsustainable energy-intensive process. As a result, there is a tendency to switch to other more energy friendly consensus mechanisms, such as Proof of Stake (PoS). Ethereum, the second most capitalised blockchain and the currently most deployed blockchain technology for energy applications, is transitioning from PoW to PoS[5].

The electricity consumption associated with PoW crypto mining has increased throughout 2021 and shows no sign of decreasing. Along with Ethereum, other blockchain networks plan to switch to - or already feature- Proof of Stake or other less energy intensive consensus mechanisms.

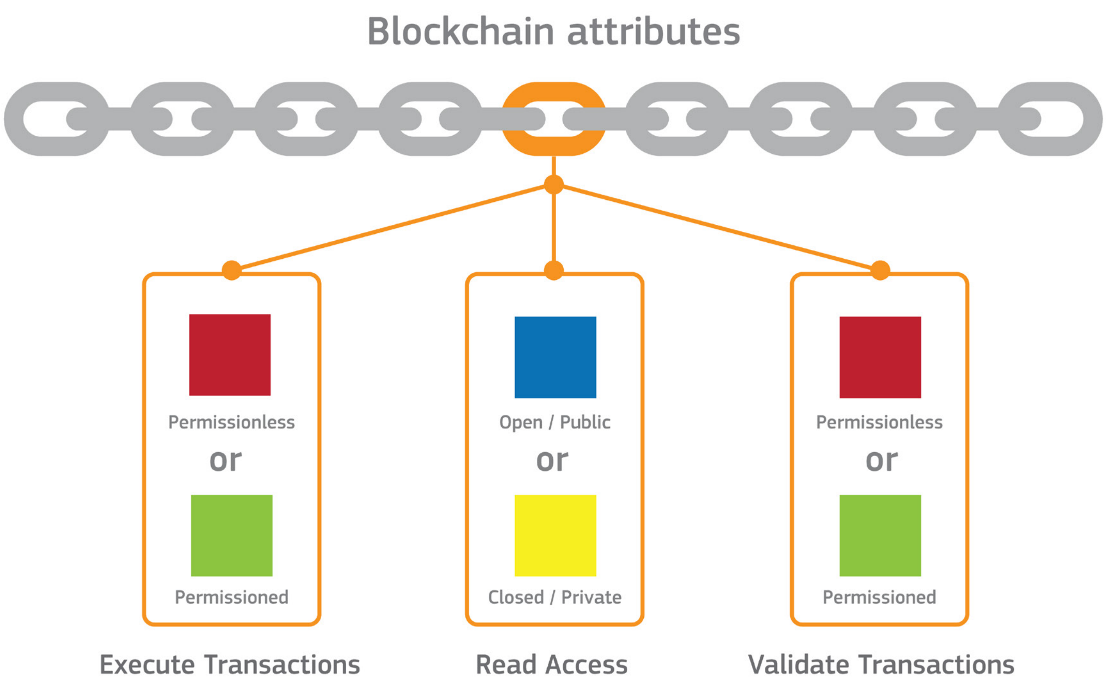
There are several other consensus algorithms besides PoW and PoS, such as proof of activity, proof of burn, proof of capacity etc. This report does not aim to provide a full overview of all the existing consensus mechanisms. However, it is important to underline here that, contrary to common belief, less energy-intensive consensus mechanisms do exist and are very mature [23].

Smart Contracts

One of the most intriguing features that have been added in new generation blockchains is the notion of smart contracts.

A smart contract is a computer program that is capable of executing/enforcing a predefined action/agreement using a blockchain, when and if specific conditions are met. Its main goal is to enable two or more parties to perform

FIGURE 4
Blockchain attributes for the different types of access
Source: EC



NOTES

[5] The electricity consumption associated with PoW crypto mining has increased throughout 2021 and shows no sign of decreasing. Along with Ethereum, other blockchain networks plan to switch to - or already feature- Proof of Stake or other less energy intensive consensus mechanisms.

a trusted transaction without the need for intermediaries. Moreover, smart contracts inherit the characteristics of blockchains and thus have no downtime, censorship or third-party interference.

Performance

Different use-cases might require different levels of performance in order to be effective and deliver their service. Hence it is important, when considering the use of blockchain technologies, to evaluate if their performance is adequate to what is needed by the use-case. The performances of blockchains are typically influenced by a few key parameters, such as the size of the block (which determines how many transactions can be validated in one shot) and the execution time (the time lapse between the moment a transaction is sent from the client until it is inserted in the blockchain). Different blockchain systems have very different approaches to validation and block size definition. As a result, execution times may vary from a few seconds to several minutes.

Following this basic overview of blockchain technologies, in the following section describes how blockchain technologies could speed-up the digitalisation of the energy sector.

4. HOW BLOCKCHAIN CAN SUPPORT ENERGY DIGITALISATION

Although blockchain seems to be generating the most buzz in financial services, the networked infrastructure of the energy industry makes it particularly suited for blockchain technology applications. And with the rise of Internet of Things, the entire energy industry may soon find its operations transformed into a vast global network of connected devices all feeding digital data into blockchain-enabled platforms that can capture and share information in real time.

Blockchain could play an innovative role in contributing to the implementation of these aspects. For instance, blockchain has features that promise to innovate the energy sector through the deployment of new grid management and business models leveraging on decentralisation, transparency, integrity and disintermediation. The expected result is the creation of a better performing grid management infrastructure and new business processing applications at the service of European industry players and consumers operating across centralised and decentralised grid frameworks.

Moreover, blockchain applied to the energy sector has the transformative potential to reduce both operational and transaction costs while simultaneously increasing trust levels among stakeholders by offering a single source of truth. For instance, there is ongoing experimentation to test Blockchains for improving the procedures for network management and security related to actors such as Transmission System Operators (TSO)[6] , Distribution System Operators (DSO)[7] in charge of electrical energy production and distribution and in the context of Distributed Energy Resources (DERs)[8]. Nevertheless, a coordinated approach to manage security risk is necessary in order to be sure that new grid management and business applications are built and marketed following security-by-design principles and related incentive structures.

Blockchain, which involves decentralised transaction verification, will potentially empower individual customers to trade power and make payments in a seamless way.

Digitalisation can help with improved network and congestion management, assisting with the renewable generation intermittency problem, allowing more effective network monitoring and more efficient network operation. It also provides digital platforms for demand response, and Peer-to-Peer (P2P) energy and carbon credit trading [21].

NOTES

[6] TSOs are entities entrusted with transporting energy in the form of natural gas or electrical power on a national or regional level, using fixed infrastructure. See Chapter III of the Electricity and Gas Directives (2009):

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0073&from=EN

[7] DSOs link bulk electricity production and transmission to end consumers - https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/distribution-system-operators-observatory-2018

[8] Conventional power stations, such as coal-fired, gas, and nuclear powered plants, as well as hydroelectric dams and large-scale solar power stations, are centralised and often require electric energy to be transmitted over long distances. By contrast, DER systems are decentralised, modular, and more flexible technologies, that are located close to the load they serve, albeit having capacities of only 10 megawatts (MW) or less.

5. ENERGY INDUSTRY BLOCKCHAIN PILOTING LANDSCAPE

To understand the magnitude of the blockchain potential in the energy sector, the Joint Research Centre of the European Commission performed a landscape analysis of the related industrial initiatives in the energy sector. This analysis clearly showed that industrial actors in the energy domain are seriously investing in blockchain technology pilots and tests. The primary goal of the analysis was to define a taxonomy of use cases in this field. Four main classes of use-cases on Blockchains for the energy sector have been identified and are described in the next subsections. The taxonomy comprises various types of use-cases totalling 117 initiatives (see Figure 5) concentrated mainly in the European Union (65), the USA (14), and Switzerland (9), with the rest scattered around the world. More than half of them, i.e. 67 are deployed at least at the proof-of-concept level.

In particular, there are 16 research initiatives and multi-purpose blockchain platforms for the energy sector. Further, there are 17 companies operating in the field of blockchain wholesale energy trading while 11 operate in the sector of blockchain wholesale energy supply and some do both. 6 companies offer flexibility services and 4 offer imbalance settlement products. Moreover, 13 companies are active in the blockchain-based smart metering domain and 9 offer Internet of Things and smart devices solutions.

However, the majority of the companies and initiatives (40 of them, a third of the total worldwide) are focused on P2P energy supply and trading. Their aim is to test and market new grid management and business applications that blockchain promises to offer. For instance, 11 companies offer blockchain based billing services. As another example, business models and investment vehicles such as Initial Coin Offerings, the issuance of digital tokens redeemable by investors in new crowdfunded ventures, are finding applications also in the energy sector. There are 25 initiatives in this domain.

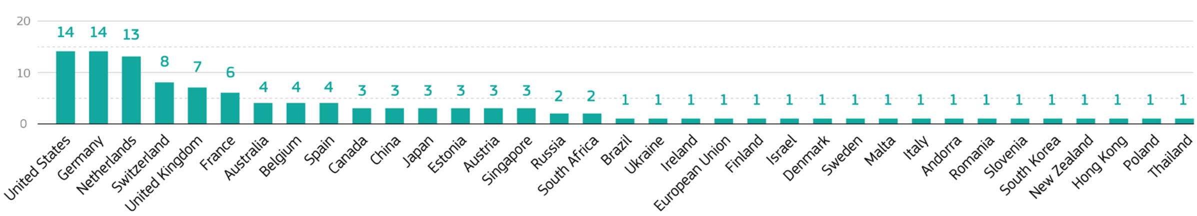
Finally, there are niche markets such as blockchain for e-Mobility (7 companies) and for asset management within environmental attributes markets. In particular, there are 5 companies working within the certification of ownership and the proof of origin market segments, while 10 offer blockchain based solutions to manage green certificates and carbon credits.

In terms of the platforms used (as Figure 7. illustrates), and according to the available data, almost half of the initiatives are tested and operated on the Ethereum blockchain (50), followed by Hyperledger (8), Tendermint (4), Tolabla, (3), Multichain and Pylon Coin (2), native blockchains (4) and many opting for one

FIGURE 5

Energy blockchains initiatives distribution per country

Source: EC



of the myriad of blockchain solutionspopulating the industry.

This bird's eye view on the state of the blockchain industry in the energy sector provides a preliminary set of observations to take into account while reading the following subsections. Although there is not a one-size-fits-all blockchain available to support the requirements of different use-cases, there is not however any direct correlation between the types of use-cases and the platform selected to deploy them by different initiatives and sectors. In particular, there is no evidence suggesting that a certain type of blockchain platform is more or less technically adequate and performing in order to serve the needs of a particular use-case or sets of use-cases instead of another.

Nevertheless, Ethereum [7] is the platform selected by more than half of the use-cases. This can be explained by the fact that Ethereum is the second most acknowledged cryptocurrency by market capitalisation after Bitcoin [8]. Moreover, Hyperledger [9] follows Ethereum arguably because it can count on IBM and then the Linux Foundation to gain widespread credibility and usage as an enterprise oriented blockchain ecosystem.

For the rest of the platforms listed above, the rationale for selection most probably depends on subjective factors and non-linear industrial dynamics influencing decision-making processes by use-case proponents. Indeed, the global blockchain industry does not currently offer reference standards supporting an objective selection of a blockchain solution instead of another in that there is not a dominant blockchain design in the industry (see section 7 for more details on this topic).

In the analysis conducted, it emerged how blockchain is seen by industry as a potential means to enhance TSOs and DSOs network management capabilities by automatically maintaining verifiable data on network assets that can autonomously transact with each other.

In this context, blockchain could help dis-intermediate the industry by transforming Transmission System Operator (TSO) and Distribution System Operator (DSO) roles of top-down energy providers – and possible single points of trust and failure in the energy supply chain – into peers operating in a horizontal network where also producers from Distributed Energy Resources (DER) could freely interact with both industry and retail players.

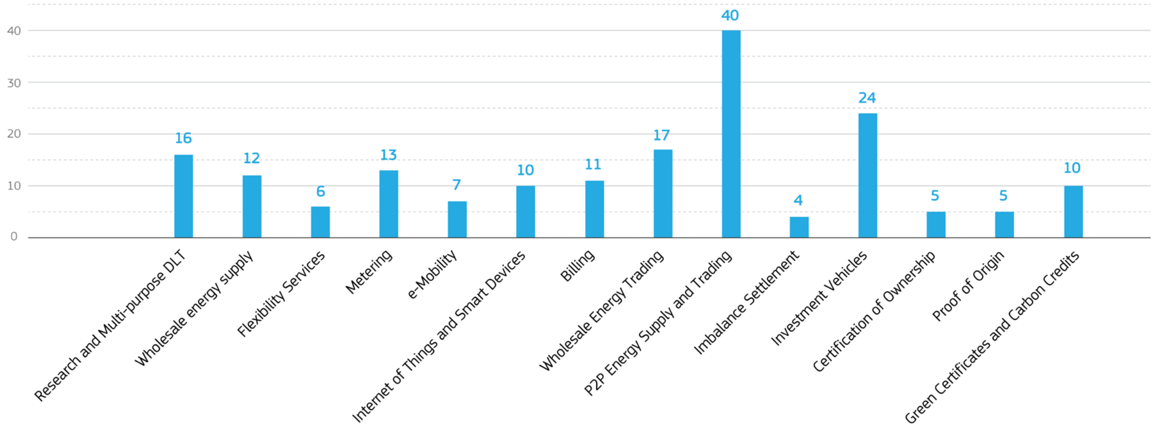
In turn, blockchain could be deployed to solve new problems created by the interaction among traditional energy suppliers and producers from distributed and renewable energy sources. The actors in the industry are conducting research on blockchain properties to improve confidentiality, integrity, and availability in the grid management services delivery.

One of the main domains of grid management, where tests are being carried-out, is smart metering, i.e. the increase of software

FIGURE 6

Blockchain project types in energy sector

Source: EC



implementations to give intelligence to electricity meters. blockchain is one of the implementations that many industry players are exploring since it could offer data authenticity, integrity and asynchronous timestamping to optimise grid operations.

Another grid management niche wherein blockchain has been prototyped is electric mobility, or e-Mobility. Alongside Artificial Intelligence, blockchain smart contracts implementations have the potential to revolutionise the automotive industry together with the business environments of many other connected industries, e.g. public administration and insurance.

Expanding the landscape analysis taking into consideration the nexus between Internet of Things and blockchain, this project highlighted another potentially disruptive aspect: in the energy domain, blockchain might have, for example, the potential to reformulate the relationships among humans and machines with the mediation of automated transactions of a different kind: energetic (energy availability), economic (energy pricing), environmental (weather forecasting), etc.

On a completely different level, many energy players are exploring blockchain at the level of financial and business applications. In this domain, many of the business cases, typical of the FinTech world, are translated in applications for investment and value transfer backed by electricity.

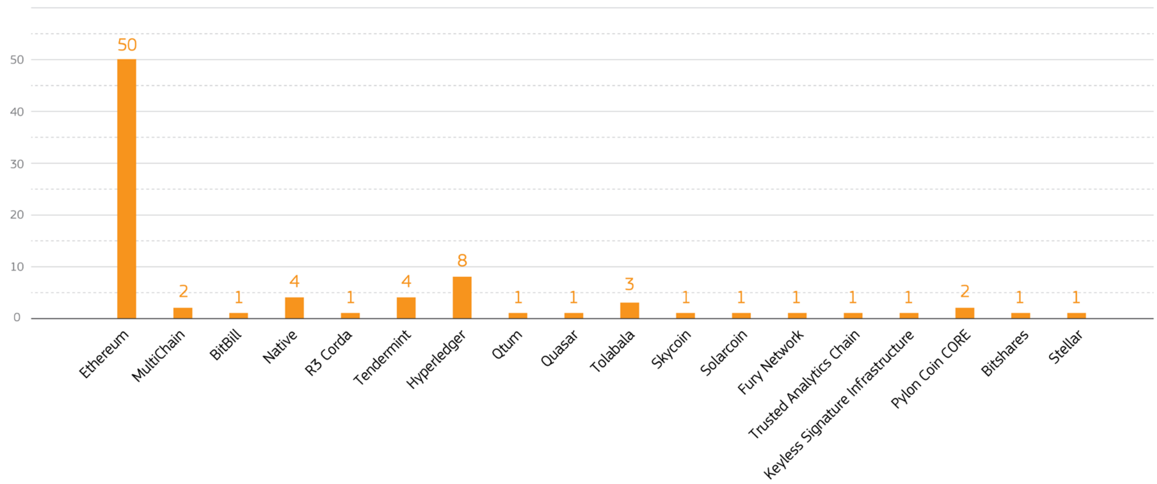
As metering is a central component in grid management, the same applies to billing as it can be thought of as its business counterpart. In fact, cryptocurrency transfer is a property of blockchain that is leveraged by both utilities and proponents of customer-centred business models in the energy sector, both in advanced economies and less developed countries.

As a subset of billing, a few actors in the power system industry are exploring the potential of blockchain to address the widespread problem of imbalance settlement. It could indeed help to manage trust and energy value flow in time, by addressing inefficient and suboptimal approaches to reserve dimensioning, while increasing consumer protection, and optimise consumption and cash flow capabilities of all stakeholders involved.

These considerations can apply also to wholesale energy trading practices. In this case, blockchain technologies can disrupt the industry by offering higher level of automation and disintermediation in an untrusted environment where the boundary between wholesalers and retailer would blur. Proponents of blockchain in these types of use cases advocate for the deployment of blockchain for the reduction of both transaction and operational costs in the transfer of energy and economic value in the industry.

Moreover, according to the vast majority of initiatives analysed, the division among

FIGURE 7
Blockchain platforms used in different energy projects
Source: EC



wholesalers and retailers, producers and consumers would further decrease. Indeed, the case for blockchain applied to the physical exchange of electricity and money peer-to-peer is considered as the most challenging, while potentially most disruptive for the industry. There are a good number of initiatives that provide blockchain investment vehicles, such as Initial Coin Offerings, to experiment especially in the Distributed Energy Resources (DER) and renewables domains.

Finally, the landscape analysis examined proposals for blockchain applications for asset management (of e.g. renewable generation, fossil based plants and other climate-friendly or -altering assets). In these cases, the blockchain inherent properties, such as distributed architecture, time-stamped, cryptographically secured and tamper-proof transaction history, can offer tools for asset certification, proof of origin of energy production and green certificates and carbon credits trading.

To our knowledge, there is not a standardised and solid framework for the deployment of blockchain at the grid management and business application levels. Security properties do not yet offer mission critical levels of performance, especially to take products from the prototyping stage to real world in production environments at a mass scale. However, as it emerged from the landscape analysis and survey data, more research and development is underway.

Nevertheless, the survey conducted among energy stakeholders confirmed the interest in blockchain application within the energy sector, in particular to support uses cases in (a) local energy communities (microgrids) and P2P marketplaces (b) decentralised exchange, (c) retail electricity markets, (d) flexibility services and proof of origin of supply or demand.

6. MOST PROMISING USE-CASES AND EXPERIMENTAL RESULTS

On the basis of the landscape analysis presented above, and taking into consideration the technical constraints of blockchain technologies, it was possible to determine the most relevant domains of application of blockchain in the energy sector from a policymaking perspective. These use-cases, were deployed and validated in the laboratories of the Joint Research Centre of the European Commission. The emerging considerations and evaluations are reported in the following part of this section.

In particular, five different use cases were selected for implementation, testing and analysis:

- Smart metering, billing and securityFostering of energy communities
- Certification of origin of energy production
- Support the implementation of flexibility services
- Electro mobility scenarios

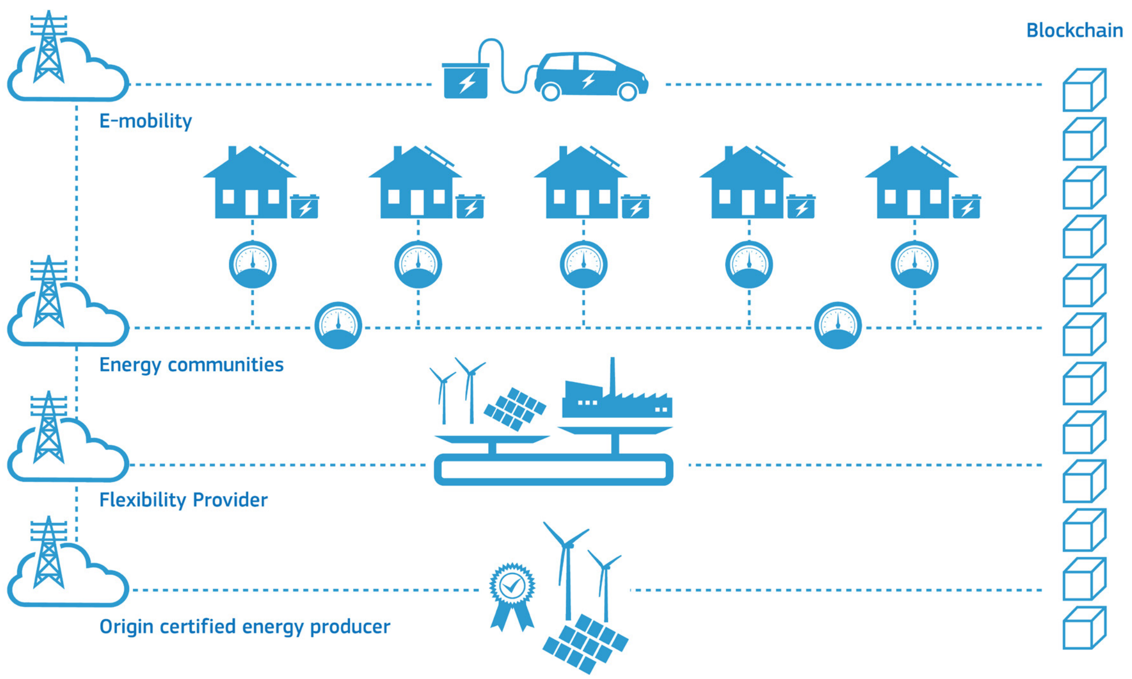
In general, these use cases are the most technically meaningful for appropriately testing and exploiting the potential of blockchain in their respective context. In addition, some of them represent either the vast majority of cases in the landscape analysis (Energy communities, with 40 projects), or can count on an appropriate regulatory framework for compliance (Flexibility services), or they were examined in order to provide scientific evidence to further inform policymaking (Certification of origin, Smart metering, Electro mobility).

This large spectrum of use-cases could be integrated into a future single system by the use of blockchain family of technologies as shown in Figure 7. In order to demonstrate the concept, we opted to use the same blockchain technology, i.e. Hyperledger Fabric, for all of our experiments.

FIGURE 8

Blockchain integration of smart energy use cases

Source: EC



Below, the selection considerations for the five use cases and the societal challenges that they address are described. Then, the technical implementation details of the load flexibility services, the e-mobility grid integration and the energy communities use-cases are presented. These use cases were implemented in JRC laboratories in order to prove their logical and technical feasibility. Based on the results of the various tests performed in all implementations, how a blockchain implementation affects the selected use-cases is evaluated. The difficulties faced are explained along with potential issues to take into account for future developments. Moreover, as a vital part of such use cases is security, possible attacks and measures to defend against them are analysed in detail.

Finally, together with smart metering, the certification of origin use-case were not tested in isolation, because they should both be seen as conditions of possibility of the three tested cases on flexibility services, electro mobility and energy communities. Each of these use-cases are presented below.

6.1 Smart metering, billing and security

One of the most critical enabler components of a smart grid are the smart meters, which are electronic devices that register real-time consumption and generation of electricity, in a household or an industry, and send the data to the electricity retailer for monitoring and billing. Smart meters play a key role in the smart grid, since they can provide useful information about the consumption and the consumer profile, which can lead to load prediction and load peak reduction.

Smart metering is considered a core service for any use-case to be supported by blockchain technologies, as smart meters data would be distributed to all the involved parties. When integrated with metering infrastructure, blockchains provide the opportunity for automated billing in energy services for consumers and distributed generators, which comes with the potential of administrative cost reduction. Blockchain offers traceability of energy produced and consumed at each end point informing consumers about the origins and cost of their energy supply, making energy charges more transparent [15].

Blockchain, by design, provides data authenticity, integrity and immutability satisfying the corresponding requirements. However, users' privacy is platform-independent considering that the smart meter data frequency collection could be adapted. One of the most challenging aspects for smart metering is communication technologies interoperability supported by smart meters. Enforcing Internet Protocol (IP) over the underlying communication system of smart meters could facilitate their blockchain integration.

Considering the policy-related requirements blockchain systems can support the provision of both non-validated near real time and historical consumption to consumers and fulfil this way the corresponding requirement. Finally, as far as the data portability is concerned though definitions of the proper data structures are technology neutral, blockchain can support data integrity and authenticity on the transferred data, providing an easy way to providers to validate consumers' data.

6.2 Fostering of energy communities

Today's energy distribution network has traditionally been considered as a 'natural monopoly' because the infrastructure required to carry electric energy to the final user is such a large and complex investment that is not considered economical to replicate. The same used to apply to energy production. Few large power plants were operational and the technology and investment needed to operate such infrastructure was off-limits for most citizens and companies. As a result, the electric business was initially conceived as a vertically integrated system. A single operator would take care of all the aspects of the energy value chain and the consumer would have to comply with the rules set forward by the monopolistic operator and later on by the legal regulations put in place by Member States and local administrations.

Market liberalisation however has started to de-couple the production of energy from its transport, transformation and delivery. The IoT revolution has made network connected energy metering economical for the average household and small business types. Another important factor is the availability of small-scale energy generators (photovoltaic, wind turbines, renewable thermal, co-generation etc.) which operate across Europe. The final and most recent enabling factor is the availability of more powerful and affordable energy storage. Lithium-Ion and Lithium-Polymer batteries have recently become very popular due to their decreasing cost and increasing capabilities in terms of energy density, power density, durability and reliability. Moreover, the recent boom of electric powered vehicles has brought as a by-product the availability of ample storage capacity to the household.

This technological advance has led to the creation of a new actor in the energy domain, the so-called 'prosumer'. The prosumer concept combines the traditional role of energy consumer with that of energy producer, frequently endowed with storage capability. In order for the prosumer to reap the benefits of independence, flexibility and economical gains promised by the current technological revolution, a paradigm shift is needed both technically and most importantly from the policy and regulatory viewpoints.

To this end, energy communities have been proposed in several research and innovation projects (see e.g. [10]), suggesting alternative approaches for energy exchange and trading. An energy community (see also Figure 9) can be defined as a group of users (consumers, producers and/or prosumers) who agree to locally exchange energy via physical or digital infrastructures. Those users can also directly operate (portions of) such cyber-physical infrastructure.

Depending on the needs, different architectures can be deployed:

- peer-to-peer energy exchange,
- community shared balance storage,
- peer-to-grid paradigms.

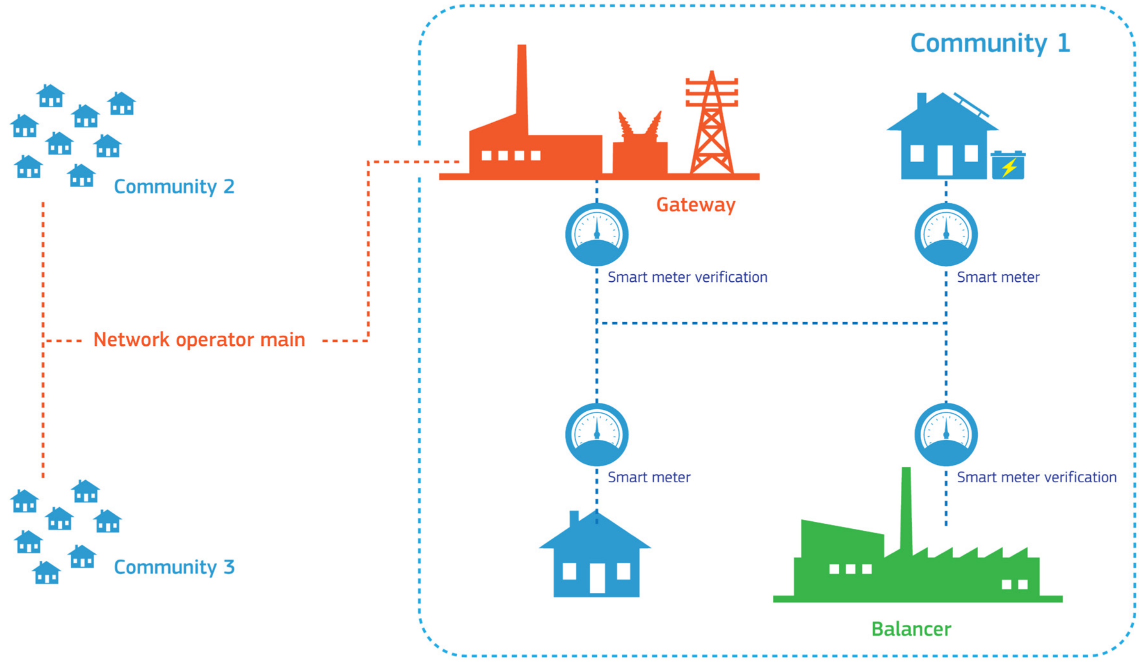
A fundamental difference between an independent peer-to-peer community and a peer-to grid configuration is that, in the former, there is no institutionalised third party mandated to guarantee proper levels of reliability and quality of supply (e.g. via synchronisation services, voltage/frequency control, load balancing, etc.).

The shared storage concept is a particular case of peer-to-peer where one or more storage units act as peers and contribute to dispatching and trading energy within the community members.

FIGURE 9

Generic structure of an energy community

Source: EC



Three societal challenges, emerging in the context of energy communities, are described below:

- Technology acceptance: the users could perceive the ICT systems as too complex to use.
- Trust in the energy community: the users could have a lack of trust in the energy community infrastructure and actors in general.
- Cost of infrastructure: the upfront technological investment needed to participate in the community (in-house electricity generation, IT infrastructure for node controller, smart meters, and energy storage technology) could be considered too high, especially when compared to benefits which will materialise at future times.

The above issues represent entry barriers for many people, who might still prefer to rely on traditional energy supply schemes.

Blockchain technologies could partially address those challenges, on one side simplifying the ICT infrastructure needed to automate such a system, and, on the other side, enhancing the level of trust, thanks to their intrinsic disintermediation and security features.

There is nonetheless the need to promote and highlight the actual benefits of building innovative technologies in the energy sector - especially in the energy community case -, in order to increase trust, and it is fundamental that the whole system is user-friendly.

A remarkable advantage of blockchain (thanks to its tokenisation and smart contract features), is the possibility to extend to a much larger user basis the possibility to invest in and trade renewable energy. Several projects show how blockchain can be used as a method to 'tokenise' renewable energy assets, services and products, thus creating new markets or business models based on co-ownership and sharing. By allowing citizens to trade the electricity freely and make revenues from it, blockchain can be a key enabler to peer-to-peer trading, and, as such, drives citizens' interest in investing in renewable energy production assets.

As far as the cost of infrastructure is concerned, since blockchain is a totally distributed system, part of the computational power investment will need to be shared among the energy system stakeholders (including energy operators and final users). Such upfront design and investment efforts might be compensated by lower operational costs. In any case, the cost of infrastructure reduced, deferred and/or covered by blockchain shall be subjected to careful cost-benefit analysis.

More generally, in order to evaluate the impact of such paradigm shift for the electricity system, new assessment methodologies shall be developed to properly capture the interactions between the different actors and technologies to value and allocate the costs and benefits. A fair allocation of (predominantly) shorter term costs and (generally) longer term benefits among the different players could help reduce uncertainties and incentivise investments.

6.3 Certification of origin of energy production

According to the EU-wide energy framework [11], energy production from renewable sources needs to cover at least 32% of the final energy needs of the consumers by 2030. Although the share of renewables in the energy mix is increasing, it is not clear to the end user whether this energy originates from renewable sources or not. The traceability of energy injections from energy producers being them renewable or not is an important aspect for the electricity transmission and distribution.

Current market structures for renewable certificates, carbon credits or general environmental attributes are fragmented and complex. Small energy producers are, in practice, excluded from claiming carbon credits due to the high costs associated with the procedure. In addition, audit processes are often performed manually by a central authority, therefore are prone to errors and even fraud. Blockchain systems can automate green certificates issuance (including for low volumes of energy) and reduce transaction costs. They could create a global market for such assets, increase transparency in the market and prevent double spending.

Certificate of origin relies mainly on smart metering functionality that can enable consumer's/prosumer's energy metering in near real time, and attribute these readings to the relevant actors for the issuance of certificate of origin. This type of data-sharing can be accomplished with the use of blockchain solutions. The generated certificate of origin should be protected against possible forgeries and all the involved parties must be able to confirm its validity.

In principle, blockchain systems can support protection against possible forgeries as the integrity and authenticity of the stored data are guaranteed and through its consensus mechanism all the participant nodes can confirm the validity of the stored data, with the immutability of the blockchain.

6.4 Support the implementation of flexibility services

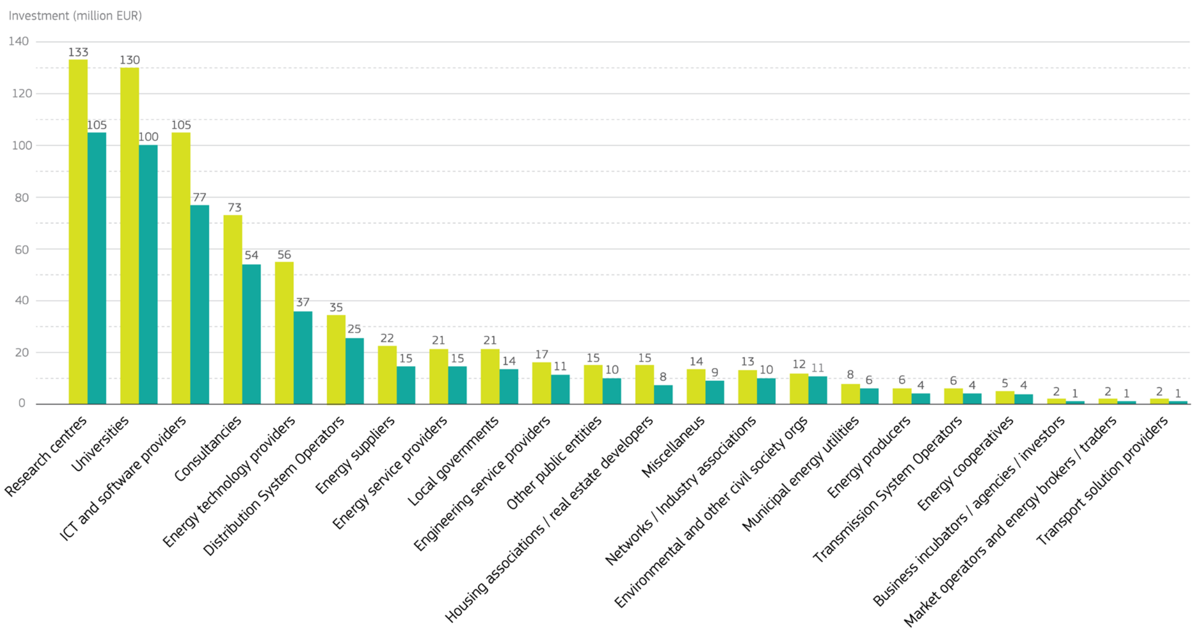
Two customer market intermediaries, namely aggregators and citizen energy communities, are defined in the 2019 Clean Energy Package (CEP) [12], with provisions on their regulatory framework, roles, and duties aiming to group the energy generation or consumption of several consumers. In this context, an aggregator is acting as an energy service provider which has the capacity to manage consumers' electricity needs and provide demand-side flexibility to the grid. Aggregation can be carried out either by traditional energy service providers such as suppliers or by new entrants such as independent aggregators. In practice, when consumers engage with an independent aggregator, they have one contract with the supplier and another one with the aggregator.

The testing and procurement of Demand Response (DR) services are becoming a reality throughout Europe and several actors are involved in Demand Side Management (DSM) research and innovation projects, as illustrated in Figure 10. The system operators currently request flexibility services to large units (mainly industrial actors) to vary their loads according to an identified need. This can be done directly or most typically through an aggregator actor that has a large portfolio of assets and coordinates the events, load triggering and settlements by taking a small fee for the service. Until now, the task of managing a few hundred loads has been manageable with traditional tools, such as Supervisory Control And Data Acquisition Systems (SCADAs), direct meter reading and transparent access of portals or platforms between aggregators and Transmission System Operators (TSOs).

In European markets, there are few examples of independent electricity aggregators engaging with commercial or residential consumers. However, with the emergence of consumer empowering, new technologies and the adequate regulatory framework, residential flexible electricity consumption will become

FIGURE 10

Share of Demand Side Management (DSM) investment by organisation type
Source: EC



more commercially attractive for aggregators and vice-versa. This will mean a higher order of magnitude when it comes to contract management, data exchange and settlements between all participants. TSOs are typically the entities supposed to request DR services, as they are in charge of assuring the grid stability. The Clean Energy Package defines the conditions under which DSOs may acquire flexibility services without distorting the markets for such services. It includes clear provisions that will enable DSOs to manage local grid issues and enhance the security of supply (SoS) through flexibility procurement.

At the level of societal challenges for flexibility services, special emphasis is put on the involvement of prosumers and citizens in the electricity market, which could unleash a trend of efficiency and a smarter use of energy. Even though no major changes to personal life would be made with large scale explicit Demand Response, some technological adaptations would have to be carried out. The system to trigger a load adjustment would have to be installed, for example. Close to real time readings would be required, as well as information disclosed, which could be seen as intrusive, showing individual's behaviour and consumption patterns. Accepted levels of comfort would have to be agreed upon with the aggregator and the cost of the required infrastructure is unclear so far.

Moreover, the financial compensation for such services is expected to be negligible and some doubts exists on how citizens could be engaged without 'significant' incentives. Social platforms with scoring mechanisms, offering complementary discounts in services could be introduced to promote the participation. Main challenges enabling large scale demand response refer also to establishing reliable control strategies and market frameworks so that the demand response resources can be used optimally.

In the context of flexibility services, opportunities for blockchain emerge such that blockchain-enabled distributed trading platforms might disrupt market operations such as wholesale market management, local trading within energy communities and flexibility service exchange within distribution grids or with transmission grids. The use of blockchain technology, with all transactions recorded in a decentralised ledger, can expedite and condense trading and settlement to nearly real-time [14].

Moreover, blockchains could assist (or even replace) human decision-making in running decentralised networks, providing flexibility services or managing power system assets. By contrast, barriers for application of this use case range from data access and use restrictions to lack of interoperability and common standards together with legal uncertainty, governance and decentralised responsibilities.

6.5 Electro mobility scenarios

Transport accounts for a quarter of the EU's greenhouse gas emissions, and still growing.

To achieve the climate neutrality ambitions stated in the European Green Deal, a 90% reduction in transport emissions is needed by 2050. Road, rail, aviation, and waterborne transport will all have to contribute to the reduction. Achieving sustainable transport means putting users first and providing them with more affordable, accessible, healthier and cleaner alternatives to their current mobility habits.

Automated and connected multimodal mobility will play an increasingly important role, together with smart traffic management systems enabled by digitalisation. The EU transport system and infrastructure will be made fit to support new sustainable mobility services that can reduce congestion and pollution, especially in urban areas. The Commission will help develop smart systems for traffic management and 'Mobility as a Service' solutions, through its funding instruments, such as the Connected Europe Facility. The demand for data capturing by automotive manufacturers is creating a shift in the traditional mobility business model.

To capture this data, vehicles are starting to have their own digital identity. For instance, the transactional data from re-fuelling at a gas station is currently on a credit card, but soon will be housed on a digital wallet owned and operated by a car. This car could generate its own income through a service model and pay for its own fuel, maintenance, and other services.

An example application scenario for this use-case is summarised as follows: we assume that the DSO faces an issue in its distribution grid, where the charger is connected. The issue could be, for example, congestion or over/under-voltage. To mitigate this issue, the DSO can use the flexibility of a Vehicle-2-Grid (V2G) connected electric vehicle (EV) by sending a price signal (or a power profile) that will trigger the car to either charge or discharge at a specific power level. Assuming that the V2G charging station is installed in an office building's car park, the signal from the DSO has to go through the Energy Management System of the building or an aggregator, which along with the building energy consumption might operate multiple charging stations in the car park, towards the specific charging station that the EV is connected to. If the EV charges, a payment will be done to the aggregator/retailer, while if the EV discharges, the aggregator will reimburse the EV owner. For the payment, a digital wallet is used and a blockchain holds the records of balancing transactions.

Other examples of use-cases on blockchain applied to e-Mobility are Fleet Management & Energy Optimisation, Autonomous Vehicles, Predictive Maintenance and features, and Smart Insurance. As shown in the next section, in our experiment, an EV was selected to perform a charging event with an integrated digital wallet or wallet app, which enabled the vehicle to make payments on its own. With blockchain, payments concerning every aspect of the car's mobility can be executed quickly, securely and automatically. Similarly to the flexibility use-case, the energy flow can be from and to the car.

6.6 Use-Case deployment and results

To better understand the potentials of the use-cases just described, they were deployed using the facilities of the European Platform for Internet Contingencies and Blockchain Analysis (EPIC-BA) and the Smart Grid Interoperability Laboratory (SGI-Lab). The detailed results of the test campaigns are reported in the specific reports. [1][2][3]

All tests were implemented over a Hyperledger Fabric infrastructure, leveraging on the scalability capability of the EPIC-BA infrastructure to test the capability of the system to manage high numbers of nodes and customers and on the stress the working boundaries up to high, on a Nissan electric vehicle (EV) with a 24-kWh battery connected to a type2 charger (<22 kW) and a storage system with 225 kW and 450-kWh capacity, which allows a bi-flow of power from and towards the grid.

Figure 5 illustrates the energy data flows for the Energy flexibility use-case.

FIGURE 11
High level architecture of flexibility use-case
Source: EC

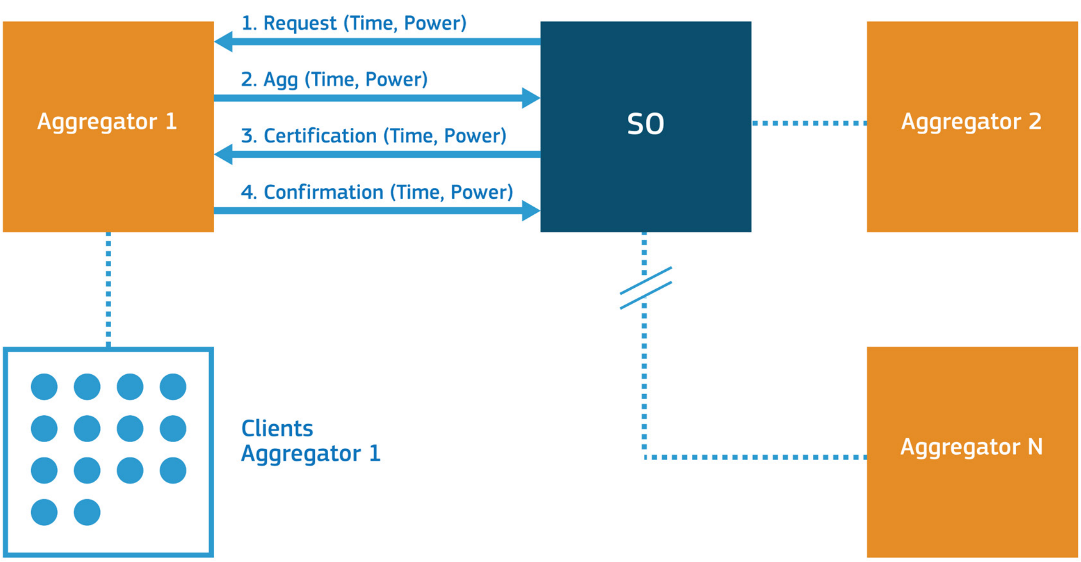


Figure 12 provides a picture of the Energy Community setting (which includes also the smart-metering use-case) and the related blockchain implementation: electricity production nodes connect with each other through a common electricity bus. Exchanges to and from the bus are recorded by a smart meter that is placed at the interfaces of each node's infrastructure (household, farm, factory etc.) to the rest of the network. Common meters owned by the community might be installed on the main line for verification purposes. Special-purpose nodes are introduced as gateways to the rest of the world and balancers for insuring stability and reliability of the grid. These balancers are basically flexibility providers.

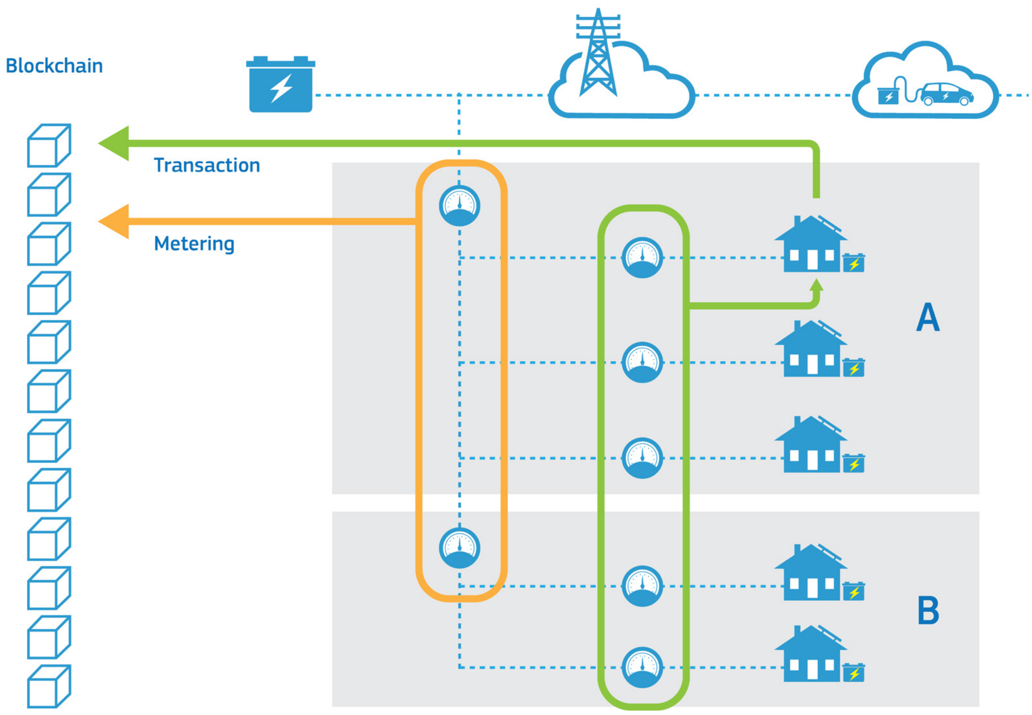
Experimental results under laboratory, showed a robust and straightforward implementation of the blockchain solution for flexibility use-case scenario (which includes also the e-mobility sub-case) as well as for energy community scenarios (including the smart-metering and source of origin use-cases). The simulations proved that these solutions can easily scale to thousands of assets.

The tests on the energy flexibility use-case demonstrated that blockchain technologies can facilitate the financial settlement and shorten the time of the settlement process in comparison to what is done presently. Moreover, it will also allow for a communication of data between the TSO and DSO which is incentivised in the Clean Energy Package. The adoption of smart contracts and facilitation of flexibility event tracing would enable large scale service provision, including medium and large assets, paving the way to citizen engagement and involvement in the energy market.

Furthermore, it should be mentioned that asset power from the same aggregator will be aggregated in the future, therefore decreasing the effort requested to the blockchain. These conditions suggest that the use of blockchain is more than capable of being implemented in a real world scenario for Demand-Response use.

For the tests conducted with the e-mobility scenario, the use of blockchains, not only allows the verification of energy provided to or taken from the grid, but implicitly allows a

FIGURE 12
Energy community test bed
Source: EC



financial settlement of the simple charging activity. Given a digital identity of the user, an integrated record of all charging activities can be performed regardless of the charging point operator, region or charging type. This would not only facilitate the payment for the user, but also allow an access to all the data generated by the charging activity of electric vehicles both for the users, charging operators and other service providers.

Given a trusted environment of the charging activity, the financial settlement does not need to be subjected to a consensus mechanism constantly. After a determined number of exchanges, the network would communicate the result of the given number of transactions as one, similar to lightning networks or side chains. Another aspect to consider is that many of the transactions (financial and non-financial such as data) are expected to be micro-transactions.

For this reason, micro-payments are one of the characteristics enabled by blockchains, that are already available already by some public projects such as IOTA or NANO blockchains, promoting a feeless machine-to-machine economy. Vehicles performing charging is just one use, but it can be applied to parking, tolls, shared vehicles, etc.

In the flexibility and e-mobility use cases testing, high throughput, in terms of number of transactions per second, has been easily reached, which has much higher performance than needed, especially considering that a real world flexibility events performs transactions in a settlement period typically lasting 15 minutes. The hardware's resources, i.e. CPU and memory, showed normal usage during the experimentation, while an important factor to consider is the network topology and the network bandwidth, especially in more complicated architectures. Moreover, with our implementation it was demonstrated that financial settlements can be facilitated in a shorter period compared to the actual situation. We also foresaw a communication between the TSO and the DSO, as is incentivised in the Clean Energy Package.

The purpose of the energy community is to offer the end user maximum flexibility in sourcing its energy needs. Thus, a node in the community can decide to buy/sell energy locally within the community or to have access via a gateway to external spot energy markets. The community itself can decide which competitive gateway and balancing services provider to use.

In term of performances and scalability, the tests confirmed the same good results obtained in the flexibility and e-mobility use-cases and that it is possible to use low-end devices (smart-meters) to communicate and send transactions to the blockchain system.

The biggest challenge in such use-cases, is how to trust the measurements and the 'digital twin' of a physical object, in this case energy. Statistical noise estimation and modelling, advanced automated instrument calibration, profiling of sensor output with artificial intelligence, are all techniques that might need to be applied in a real-world implementation.

There are of course some considerations which should be expressed. We envision that in a larger scale experiment of this type, some architectural design issues may arise. The most important, is where and how the actual blockchain system will be deployed. Since smart meters are usually not computationally powerful, it would seem inappropriate for them to host the backbone of the blockchain. A potential solution would be for households participating in the community, to host a blockchain node each.

This would also provide total transparency to the operations of the network, and in the meantime divide the operation workload. In general, all the on-field tests deployed demonstrated an overall robustness of the system, resilience to cyber-threats, capacity to scale and adequate maturity.

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7. CONCLUSIONS

This chapter summarises the main issues and outcomes stemming from the series of studies conducted by the Joint Research Centre.

Recommendations are made for addressing the issues of a wider use of blockchain in the energy sector. In conclusion, some take-away messages are highlighted.

7.1 Trends, issues and lessons learned

The main lessons distilled from the review, modelling and experimental activities carried out in this project, are as follows:

- **Blockchain is confirmed to be a versatile means to support evidence-based decision-making in the climate-neutrality and energy fields**. For example, blockchain can enable carbon credit and guarantees of origin schemes or help citizens to sell solar energy in the markets. Clearly, blockchain also needs to demonstrate that the accrued sustainability benefits outweigh the environmental footprint, especially when deployed at a wide-scale (see also the energy efficiency considerations below). The EU's Research and Innovation programmes allocate significant budget to test blockchain solutions in several sectors, including the climate and energy ones.
- Within the whole energy system, **the electricity sector is increasingly researching innovative blockchain solutions** aiming to streamline system and market operations and propose new services. The currently most deployed solutions rely on Ethereum-derived technologies, although efforts to introduce other blockchain solutions (e.g. based on Solana, Hyperledger, IOTA and others) are on the rise.
- **Several actors**, involved in energy/digital businesses or emerging from other socio-economic sectors, **show appetite for experimenting with blockchain solutions across the energy value chain**. Pilots and use-cases are flourishing in Europe (and beyond). This is particularly true, where new actors - such as the aggregators of several energy users/prosumers and automated software agents - wish to enter the energy business or many stakeholders (e.g. in the case of energy communities), with different levels of security/trust, have to interact.
- **Consumers are not yet fully engaged in digital energy projects** (many step away from pilots after an initial phase of interest) and independent aggregators still face entry barriers to participate in electricity markets (regulations and practices preventing customers to contract agreements with emerging actors are still present). The upfront technological, knowledge and education investments needed to participate in energy communities - and thus reap their benefits -, still hamper citizens' involvement and engagement.
- **Newer blockchain solutions have improved their technical performances compared to older ones**. In-house tests confirm the adequately growing performances of blockchain, in terms of throughput (speed, transactions per second), scalability (number of nodes managed) and end-to-end delay, in a wide range of use cases (from, for example, paying for an electric vehicle recharge on a motorway to using home devices to trade energy). The blockchain permission policies (linked to the reading and writing rights of the actors interacting with the blockchain) emerge as another crucial factor for the design of blockchain solutions. Under adequate techno-economic and regulatory conditions, selected blockchain solutions seem to confirm their potential to scale up to real-world scenarios. Nevertheless, **solving the so-called blockchain trilemma**, i.e. concurrently optimising the three key aspects of decentralisation, security and scalability, **remains a big challenge before moving to large-scale applications**.
- The **sustainability and energy-footprint of blockchain** remain among the most debated – but not always well-analysed/communicated – issues, even if new blockchain solutions and consensus mechanisms (i.e. the algorithms needed to run a blockchain, largely responsible for the blockchain energy-intensity) do not display energy performances worse

than those of comparable ICT systems and data centres.

- **Regulatory sandboxes testing blockchain solutions are beginning to appear in the digital energy field**. These are specific spaces with relaxed regulatory conditions where new products, services and business models can be trialled in a real-world environment.
- **Blockchain applications for higher-level energy system functionalities** (i.e. applications running on layers 'far' from the physical power grid) **are more numerous and mature**. Blockchain appears well suited to support the financial settlement of energy transactions, the energy trading in local or wider markets, the energy management and flexibility services provisioning, and several certification and billing processes. As an example, the experiments we executed in the energy flexibility use case – i.e. matching the power generation fluctuations with electricity demand injections or withdrawals – can be inferred to be scalable to thousands of assets/nodes. This is because the simulations were conducted on a per second basis, whereas the demand response settlement period typically refers to several (e.g. 15) minutes. Similar considerations apply to the electric vehicle's charging and discharging transactions as the e-mobility use case de facto extends the demand response use case.
- **Blockchain applications more linked to energy system operations** (i.e. 'closer' to and directly impacting the physical power grids, such as power dispatching) **are instead less developed**. This is mainly due to lack of adequate guarantees in terms of safety, certification, and standardisation, which are the driving requirements for the operation of critical infrastructures. To date, just a few blockchain-enabled pilots tried to take into account the whole spectrum of physical constraints involved in power system management.
- **Blockchain-enabled distributed trading platforms might disrupt market operations** such as wholesale market management, local trading within energy communities and flexibility service exchange in distribution or transmission grids. The use of blockchain, with all transactions recorded in a decentralised register, can expedite and condense trading and settlement. Such automated trading may allow for pushing trading operations to real-time, thus shortening the bidding intervals relative to current practices. This might however also bring about market concentration and distortion issues, when automated agents adopt instantaneous strategies to co-operate or compete with other agents.
- **An adequate and interoperable smart metering infrastructure emerges as indispensable for the activation of blockchain services** for energy communities and peer-to-peer energy trading. The smart metering use-case is, in a way, the foundational layer of the Energy Community use-case, representing the most straightforward blockchain use one could think of (regarding consumptions measurement, notarisation and billing). However the blockchain-readiness of smart meters, even those of the newest generations, appear somewhat limited. Access to smart meter data is also a potential barrier as blockchains use the most classical Internet protocols, and not all the meters support Internet connections.
- **Blockchain shows high potential to be deployed as the 'distributed driving brain' of an energy community**. The energy community use-case, with distributed smart meters validating transactions and smart contracts controlling the neighbourhood energy market, was the most complex to implement. Nonetheless the set-up trialled in the JRC labs, even with in-house built controllers and devices, were demonstrated to be resilient, stable and scalable.
- **Data security and integrity remains vulnerable before reaching the blockchain**. Data – once stored on the blockchain – is resilient to tampering, the data transfer from the physical world to the blockchain remains prone to vulnerability. How to be sure that a certificate of origin for a certain amount of renewable energy we want to trade is actually produced by a specific wind farm at a specific time? Or, as another example, how do we to verify that smart meters and in-home devices accurately record the amounts of energy produced or consumed?
- **Some authentication and protection rules are hard to interpret in blockchain ecosystems**, owing to the radical decentralisation of data storage and processing. As an example, once a user identity is created on the existing blockchain, there is little guarantee that the user requesting that identity is the real identity's owner and not a malicious one. This problem occurs to various degrees in

every digital platform accessed via 'soft-identity' schemes.

- **Blockchain architectures can facilitate data exchange among incumbents** (e.g. Transmission and Distribution System Operators) and/or with emerging actors (e.g. aggregators), **as called for by the Clean Energy Package**. Currently there are several limitations and constraints on the legal possibility of exploiting data in a blockchain e.g. to activate smart contracts. Blockchain pilots showed the potential advantages of automatically generating invoices and triggering smart contracts, provided that energy data is effectively accessed and used. The still embryonic stage of blockchain platforms – and in particular, of smart contracts – is another obstacle to the deployment of complex automatisms and services.
- Several pilots have shown the **urgent need for ensuring the interoperability of different blockchain solutions**, of on-chain and off-chain systems, of IoT devices and cloud-based solutions with blockchain networks. The blockchain solutions integration and interoperability with existing legacy systems, particularly to gather readings and system data, still constitutes a big challenge.
- With the growing digitalisation of the energy system, and equally so for the deployment of blockchain solutions, a **reliable Internet infrastructure** appears as a crucial requirement and a critical service to operate the digital energy grids.

7.2 Policy and regulatory recommendations

Several aspects and interfaces still must be properly understood to govern the introduction of blockchain-based electricity delivery options and services [6] [26]. To this end, a set of recommendations were identified to address issues emerging from the desktop and experimental research conducted.

SECURITY, PRIVACY & IDENTITY

- **Requirements for blockchain applications maintaining adequate cybersecurity and electricity supply security levels should be defined**. This is particularly important in the context of the Network Code for cybersecurity aspects of cross-border electricity flows, as requested by the Electricity Market Regulation. This would allow to timely identify the actual cybersecurity technological limitations and their improvement opportunities, particularly in the context of critical infrastructures.
- **Mechanisms to safeguard data security and integrity should be further developed**. A big challenge is how to trust the energy measurements and the 'digital twin' of physical objects, especially before they are saved on the blockchain. As an example, in the case of the energy metered and traded in a local energy community, redundancy mechanisms could be adopted in the smart metering measurements (i.e. deploying a common set of smart meters measuring energy exchanges independently of the household's smart meters).
- **Data should be protected by design and shared only in so far as needed to activate consented blockchain-enabled services**. Transacted data are at the core of blockchain (a blockchain is, indeed, a long chain of data). The definition of the boundaries between data sharing and protection should follow the stringent rules laid down in the EU General Data Protection Regulation (GDPR), which aims to safeguard citizens' personal data and strengthen their fundamental rights.
- **Effective integration strategies between data protection and cybersecurity initiatives should be put forward**, to ensure that personal data are well-protected, not misused and that citizens ultimately are in control of their personal data. Blockchain – a distributed infrastructure able to ensure trust among parties in place of a centralised party - offers a new perspective on the way to enforce cybersecurity measures in the digitalised energy system.
- The energy digitalisation phenomenon poses, from a cybersecurity perspective, a question on the **resilience and security of the modern telecommunication network and Internet**. From a **strategic autonomy** perspective, Internet governance and development are currently outside the control of Europe. If Europe wants to lead the digital development (relying also upon blockchain technologies), it is of utmost importance to start a deep reflection on how Europe could secure the stability and security of its 'portion of Internet', and on the way we can change

it to secure our cyber-physical critical infrastructures[9].

- **Cybersecurity certification schemes should increasingly cover both the domain of blockchain core infrastructure** and the domain of end user applications and devices (e.g. IoT). Within the context of the Cybersecurity Act and the cybersecurity certification rolling plan, the Commission could push forward an item concerning blockchain technologies, to define a cybersecurity certification scheme. This would allow for an adequate cybersecurity assurance level for what concerns the blockchain implementations in the different sectors.
- **Strong authentication schemes should be embedded in the design of blockchain solutions**. Questions related to delivering user experience while respecting individual privacy and identity should be addressed drawing upon the provisions of the eIDAS (electronic Identification Authentication and Signature) Regulation. In particular, the authentication problem of 'soft-identity' could be solved with Strong ID enrolment procedures or linking soft-id to strong-id (e.g. verifiable electronic ID documents).

DATA ACCESS, LIABILITY AND MARKETS

- **Robust energy data hubs/platforms – with consented rules for data access and use – should be designed**. This is essential for governing the interactions within an energy system hosting an increasing number of decentralised actors and resources. As an example, only by properly accessing data (particularly those linked to smart meters) can electricity customers fully benefit from competition in the retail markets and contribute to innovative flexibility services provision. Energy digitalisation should be regulated by: generating the appropriately granular (spatial and time) data on the electricity system; making data accessible, interoperable and secure for current and potential market participants.
- **Market rules should be adapted to contemplate the emergence of new actors in the form of automated agents**. The increased automated decision-making and trading on electricity or flexibility markets enabled by blockchain technologies should be carefully studied to anticipate its market efficiency, competition and security of supply implications.
- **Decentralised responsibilities of electricity supply and delivery should be clearly defined and allocated**. Disintermediation and distributed architecture are two of the most peculiar characteristics of blockchain technologies. While these features are in fact key enablers in the trusted integration of different actors in the smart-grid ecosystem, they can potentially create confusion in terms of responsibilities and liability. For that reason, a reflection is needed to establish clear rules, roles and duties in this new energy paradigm.

FAIRNESS AND ACCEPTANCE

- **Fairness should be a guiding principle for designing more decentralised energy markets not discriminating any player, be they people or businesses**. Associating the appropriate blockchain solution to the different use cases is crucial to enable different electricity market governance schemes and role types for consumers. Most of the blockchain-enabled energy projects rely on Ethereum – in permission-less or permissioned configurations – or other emerging technologies such as Hyperledger – with permissioned schemes. The permission-less design generally entails that every user contributes to manage the blockchain in a trust-less environment. However, this comes at a cost of a more expensive validation process. Permissioned applications need instead a small group of nodes to validate transactions. This allows for reducing the validation costs, as only a fewer number of nodes interact to maintain the blockchain, but also requires full trust on the validators.
- **Consumers should be further involved and incentivised to invest in blockchain projects**. Regulatory initiatives would be needed to increasingly make blockchain ad-

NOTES

[9] Other relevant EC legislative initiatives on privacy and data protection aim at strengthening the security of internet-connected devices, most of which are expected to be part of the Internet of Things, and of wearable radio equipment.

vantageous for consumers, to enlarge the community basis of those participating in the energy flexibility service provisioning and in the Citizen/Renewable Energy Communities, as defined in the Clean Energy Package. The adoption of smart contracts can facilitate such citizen engagement in the energy market. Putting the customer at the centre of the energy system, requires effort to identify and exploit the possible interfaces and synergies between different energy systems (e.g. electricity, heat, gas,...) and economic sectors (e.g. transport, health,...).

- **A balance should be found between consumer empowerment and protection**. This would be in line with the European Green Deal provisions calling for a socially just transition where the risk of energy poverty is addressed and users most vulnerable to the energy transition are protected.

SCALABILITY AND SUSTAINABILITY

- **The EU and national legislators should keep developing a comprehensive pro-innovation legal framework for digital applications**, also better regulating blockchain-enabled digital assets and smart contracts. A major regulatory challenge is to reconcile the stability of the legal framework with the rapidity to react to innovation pace. The EU should keep providing funding for blockchain research and innovation, both in the form of grants and by supporting investment in start-ups. Large-scale and multidisciplinary pilots that target integrated architectures, interoperable applications, and harmonised standards are still needed to test the merits and challenges of blockchain use-cases and applications.
- **Regulatory experimentations should be further adopted** to address the blockchain technological trilemma (i.e. optimising blockchain decentralisation, security and scalability) and ensure the adoption of approaches fit for purpose and future-proof. Supporting responsible innovation via **pilot regimes and regulatory sandboxing** might help removing obstacles to the application of new technologies and promoting technology uptake. Reporting mechanisms on blockchain pilots – including cost-benefit and risk analyses - would be sharing knowledge and best practices. **The EC and the European Blockchain Partnership are setting up a pan-European regulatory sandbox** tackling data spaces, smart contracts, and digital identity, and covering also the energy sector (among other sectors such as finance, health, environment etc).
- **Analyses on the energy footprint of the blockchain solutions** under testing/deployment – both in terms of absolute consumption and energy mix (renewables, fossil, etc...) anticipated to cover such consumption – **should always accompany the studies on the scalability and performance requirements. Fair cost-benefit analyses** weighing the benefits with the costs and adequate communication campaigns may help to better understand opportunities and threats.

INTEROPERABILITY AND STANDARDS

- **The EU and Member States stakeholders should continue being involved in the work of international standard organisations** such as ISO, ETSI, CEN-CENELEC, IEEE and ITUT, and should continue engaging with other relevant bodies globally such as INATBA (International Association for Trusted Blockchain Applications), covering solutions for energy digitalisation in general and blockchain integration in particular.
- **Proper standards and interoperability of blockchain-enabled devices (including meters, sensors, appliances) should be promoted**, as this might help developing markets for demand response, distributed energy resources and flexibility services. Guaranteeing interoperability, standardisation and blockchain-readiness of the smart metering infrastructure is particularly important as smart meters enable virtually all the services put forward by blockchain technologies. The EC implementing acts on interoperability requirements and transparent procedures for access to data (as called for by the Electricity Market Directive) might tackle some of the above aspects. Standardisation would also be extremely important to ensure a common minimum level of cybersecurity of blockchain platforms. Standardisation initiatives would pave the way toward interoperability which, in mission critical infrastructures, is a key factor to ensure technology diversity and resilience against cyber-attacks. Establishing standards for interoperability across industries will also be pivotal as the power sector becomes more coupled with adjacent sectors such as the transportation, heating, and others.

7.3 Final remarks

The EC Digitalisation of Energy Action Plan represents a powerful toolbox to implement actions for a wider deployment of digital technologies – including blockchain – in the energy sector. The Action Plan aims to develop a competitive market for digital energy services that ensures data privacy and sovereignty and supports investment in digital energy infrastructure. This Plan could accelerate the implementation of digital solutions, building on the Common European energy data space aimed to promote a stronger availability and cross-sector sharing of data, in a customer-centric, secure and trustworthy manner.

While the digital transformation is a key enabler to reach the climate-neutrality objectives, a consistent approach in the regulation of several cross-cutting sectors (energy, transport, finance etc.) is equally needed. Recently issued regulation proposals in the digital finance/crypto-asset sectors contain interesting approaches and solutions, which could be applicable to or of inspiration for the energy sector as well.

It remains to be seen to what extent blockchain can support or subvert business models in the transitioning electricity systems and markets. Indeed, blockchain represents only one of the technologies enabling power system innovation, to be combined with other digital technologies (including Artificial Intelligence, big data, IoT), to achieve the climate-neutrality and sustainability targets.

In this context, one of the main challenges for policy decision makers, is to strike a balance between supporting innovation, protecting consumers and upholding market integrity.

The Joint Research Centre (JRC) smart grids and cybersecurity laboratories stand ready to scale up their research activities in support of policy decision making, with a view at identifying critical issues in the deployment of blockchain-enabled sustainable energy solutions.

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List of abbreviations

DER	Distributed Energy Resources
DLT	Distributed Ledger Technology
DSM	Demand Side Management
DSO	Distribution System Operator
DR	Demand Response
EC	European Commission
EPIC-BA	European Platform for Internet Contingencies and Blockchain Analysis
EU	European Union
EV	Electric Vehicle
IEA	International Energy Agency
ITRE	Industry, Research and Energy Committee of the European Parliament
JRC	Joint Research Centre
P2P	Peer-to-Peer
PV	Photovoltaic
SCADA	Supervisory Control And Data Acquisition
SGILAB	Smart Grid Interoperability Lab
TSO	Transmission System Operator
V2G	Vehicle-to-Grid

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KJ-NA-31008-EN-N

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Publications Office of the European Union

doi:10.2760/62246

ISBN 978-92-76-49089-0