Chapter 3

c0015 # Transition toward blockchain-based electricity trading markets

Mohamed Lotfi[a,b], Cláudio Monteiro[a], Miadreza Shafie-Khah[c] and João P.S. Catalão[a,b]

[a]*Faculty of Engineering, University of Porto, Porto, Portugal,* [b]*INESC TEC, Porto, Portugal,* [c]*School of Technology and Innovations, University of Vaasa, Vaasa, Finland*

s0010 ## 1. The rise of blockchain

p0010 It may be surprising to recall that blockchain was unheard of merely a decade ago. Being first launched in 2008 in the advent of Bitcoin, it is indeed astounding how the technology rapidly became a major enabler of all sorts of decentralized platforms, which are now ever so important in this digital era of extensive Internet-of-Thing (IoT) enabling. In order to understand how blockchain-based systems took center stage in modern electricity trading frameworks, it is necessary to look back at the sequence of events which resulted in the need for blockchain, its creation, success as the first fully decentralized commercial platform, and subsequent expansion to the energy sector.

p0015 In fact, blockchain seems to have emerged at the most convenient timing for the energy sector, which in itself was transforming in favor of more decentralized structures and decision making. Therefore, blockchain appeared as a reliable solution to several challenges facing the energy sector, and with perfect timing. That being said, this convenience is absolutely no coincidence. These simultaneous events happened, and continue to happen, in the context of a much larger revolution, the fourth industrial revolution.

s0015 ### 1.1 The fourth industrial revolution

p0020 Previous industrial revolutions all had one thing in common: each of them was triggered by a uniquely identifiable technological breakthrough. Steam engines fueled mechanization in the first, electricity sparked mass production in the second, and electronics and computers made automation possible in the third.

Blockchain-based Smart Grids. https://doi.org/10.1016/B978-0-12-817862-1.00003-8

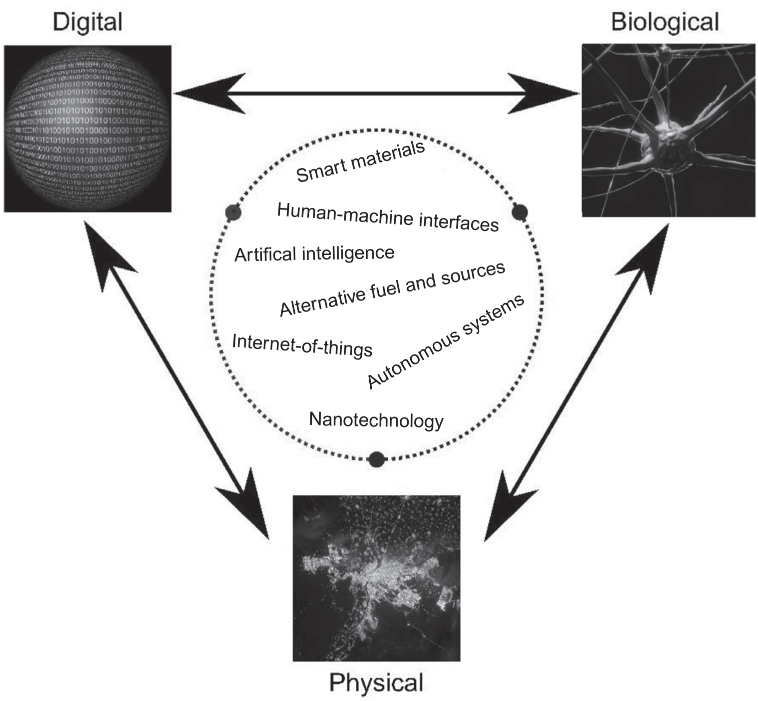
B978-0-12-817862-1.00003-8, 00003

The fourth industrial revolution currently underway is prominently different from its predecessors for two main reasons.

p0025 First, it was not triggered by a single breakthrough; rather it is the result of a combination of simultaneous technological and scientific advances. By increasingly overlapping digital, physical, and biological systems, it is giving rise to cyber-physical systems (CPS) [1]. These fourth generation industry systems (I4.0) are designed based on the following principles [2]:

- u0010 decentralized decisions;
- u0015 information transparency (data analytics and information provision)l
- u0020 interoperability and interconnection; and
- u0025 technical assistance (e.g., virtual assistance) (Fig. 1).

p0050 The second difference between the fourth industrial revolution and its predecessors is the rate at which technological advance has been occurring. With an exponential rate rather than a linear one, it continues to be disruptive to almost all industries globally. This often left decision and policy makers significantly lagging behind, often being caught in "traditional, linear (and nondisruptive) thinking" [3, 4]. As such, the transfer of novel innovative solutions between



f0010 **FIG. 1** The fourth industrial revolution: a synergy of simultaneous technological breakthroughs contributing to the rise of CPS by overlapping digital, physical, and biological systems.

Shafie-khah, 978-0-12-817862-1

B978-0-12-817862-1.00003-8, 00003

different sectors which are facing similar emerging challenges is often delayed. The adoption of blockchain by the energy sector is a perfect example of this. Having first appearing as an enabling technology for decentralized commercial systems, it took time to attract the attention of the energy sector which at the time was struggling to find a solution to manage increasing decentralization caused by proliferation of micro-generation and the rise of small-scale prosumers. In this chapter, we present the concurrent events which lead to blockchain now being a key enabler of peer-to-peer energy trading and show the exact series of milestones leading to the current status.

s0020 1.2 An interconnected world: The rise of the Internet-of-things

p0055 In its earliest days, the Internet was originally developed to connect and transfer data between computers. With the advent of smartphones (technically small computers), the Internet became a network which also provided nonstop connectivity between people. As electronics and IT evolved, “things” which are not by nature computing or communication devices started being connected to the Internet. The term “Internet of Things” started circulating around 2003 but was first officially used in 2005, when the International Telecommunication Union published a report titled “Internet of Things,” describing the rise of IoT as follows [5]:

Q0010 > *developments are rapidly under way to take this phenomenon an important step further… enabling new forms of **communication between people and things, and between things themselves.** A new dimension has been added…: **from anytime, any place connectivity for anyone, we will now have connectivity for anything.***

p0060 This changed everything. The emergence of IoT propelled global interconnectedness to an unprecedented level, opening the door for previously inconceivable possibilities for technological, social, and economic advancement. The IoT has been one of the main technologies driving the fourth industrial revolution.

p0065 More than a decade later, IoT continues to grow at an exponentially increasing rate. In 2016, there was a total of around 17.6 billion devices connected to the Internet of which 11.2 (64%) are conventional devices such as smartphones and laptops while 6.4 (36%) are other devices, “things,” such as appliances, meters, etc. [6]. In a press statement, Gartner stated its prediction of the latter figure (nonconventional devices/things) growing to 20.8 billion by 2020 [7]. IDC published a market forecast which put this number at 28.1 billion. Ericsson and IHS have both published reports forecasting the total number of Internet-connected devices (conventional and things) at 28 and 30.7, respectively [8, 9]. By analyzing those numbers (Table 1), one can see that the number of new “things” to be IoT connected will increase dramatically by 225% (by most conservative forecasts), compared to a mere 60% growth in the overall number of IoT-connected devices.

t0010 **TABLE 1** **Number of IoT-connected devices and a summary of predicted changes from 2016 to 2021.**

Type of device	IoT connected in 2016 (billion)	IoT connected in 2021 (billion)	Percentage change
All	17.6	28 (Ericsson) [8] 30.7 (IHS) [9]	+60% ⇔ +75%
Conventional (computers, smartphones, etc.)	11.2	7.2 (Ericsson/ Gartner) 2.6 (IHS/IDC)	−35% ⇔ −75%
"Things" (appliances, sensors, etc.)	6.4	20.8 (Gartner) [7] 28.1 (IDC) [10]	+225% ⇔ +340%

p0070 This rapid uncontrollable growth of IoT is unleashing unprecedented data traffic on the Internet, creating two main problems: *data redundancy* and *data security/privacy*. In an IoT stakeholders survey [11], 41% of respondents said "timely collection and analysis of data" was a major challenge since there was "too much data to analyze effectively," "difficult to capture useful data," and "data is analyzed too slowly to be actionable." Those responses precisely describe the data redundancy problem in modern IoT-enabled systems.

p0075 A major solution effort to data redundancy was the development cloud computing. IoT refers to the connection of devices to the Internet and cloud computing refers to how those devices work together to deliver data, applications, or services [12]. IBM defines cloud computing as the "delivery of on-demand computing resources… over the Internet on a pay-for-use basis" [13]. Another effort to tackle the data redundancy problem has been the development of more advanced and efficient distributed data analysis algorithms.

p0080 In fact, it is interesting to see that according to all forecasts the number of conventional devices is expected to decrease, despite the enormous overall IoT growth. This can be attributed to the fact that with the increased use of things like smart sensors or smart actuators, the need for many computers currently used solely to provide the Internet link for such devices will cease to exist. In addition, the emergence of cloud computing and more advanced data analytics will facilitate shared processing and storage resources, reducing the required number of dispensable computing and storage devices.

p0085 As for the second (security/privacy) problem, it is hardly possible to come across any IoT-related discussion without the mention of the topic. With everything from personal appliances to industrial machinery being connected

B978-0-12-817862-1.00003-8, 00003

to an extended global network, the potential damage of cyberattacks and unsolicited disclosure could be devastating. It is therefore not surprising that another report by Gartner [14] predicted that IoT security spending growth is set to overtake overall IoT spending growth by 2017, which was an impressively accurate prediction. In the survey of IoT stakeholders mentioned earlier, the top challenge in IoT projects reported by 58% of respondents was "Business processes or policies" in which they complained that privacy concerns over confidential data posed a major issue preventing data collection [11]. The approval of the European Union's General Data Protection Regulation (GDPR) in 2016 [15] and other similar legislation worldwide made data security and privacy not only a concern, but also a legally binding obligation for all sectors affected by IoT enabling.

p0090 Those sectors were therefore expected to explore and implement novel solutions to address data redundancy and security issues. While the issue of data redundancy was quickly handled early on, privacy and security issues remained a major concern. This was due to two reasons. One of the main reasons for this is the fact that the latter is not only dependent on the availability of feasible technical solutions, but also involves social, political, and economical debate.

p0095 The energy industry is and will continue to be one of the most affected by the growth of IoT. Of the 20.8 billion nonconventional devices expected to be online by 2020/2021, around 1.4 billion will be from the energy industry, and 1.5 billion from home energy management devices. This meant that 10% of all IoT endpoints will be energy or energy management devices. Therefore, the energy sector began to realize in that period that incorporating compatible and feasible solutions for both data redundancy and privacy problems will be a necessity for the design future energy system structures in an IoT-dominated world.

p0100 This unstoppable IoT enabling of energy systems on all levels reinforced an increasingly popular vision in scientific literature: the Internet of Energy (IoE). This vision of IoE being the product of IoT enabling of smart grids (SGs) was first mentioned in 2010 [16]. The article envisioned scalable and self-sufficient energy networks through Internet enabling. Computational power required for coordination and management of energy supply and demand is provided by cloud resources. The other stated requirement was sufficient energy storage resources, which is becoming increasing efficient and affordable. As such, scientific literature started showing great attention to this IoE paradigm [17–23] with multiple other associated variants such as Local Area Energy Networks (E-LAN) [24] and Smart Grids 2.0 [25].

p0105 The consensus in scientific literature was that technical models and processes developed in an IoE paradigm should be: (1) distributed (fully decentralized), (2) efficient at data analysis (with efficient forecasting and optimization capabilities), (3) scalable, and (4) user-friendly (plug and play) [20, 23]. Those correspond exactly with design requirements listed earlier, making this IoE framework a perfectly suitable as an I4.0 solution model.

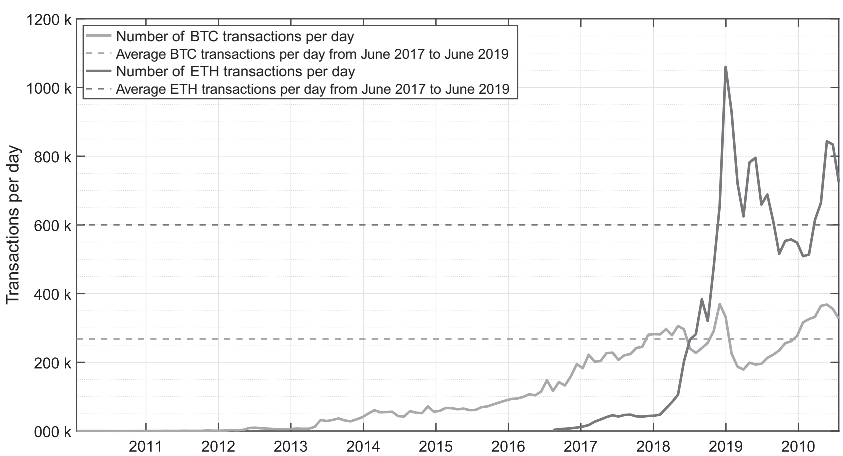
B978-0-12-817862-1.00003-8, 00003

s0025 1.3 Decentralized economies: The success of blockchain

p0110 Following the 2008 global financial crisis, the world's first digital cryptocurrency (Bitcoin) was proposed [26]. The introduced platform allowed peer-to-peer (P2P) transactions to take place, eliminating the need for intermediary financial authorities, being the first fully decentralized commercial system of its kind. It was a tremendous success. In 2010, 1 Bitcoin was valued at 0.08 USD, and rose exponentially to reach a peak value of 17,000 USD in 2017, maintaining a market capital well above 100 Billion USD since then. This astonishingly rapid success is primarily attributed to the underlying technology: blockchain, a cryptographically secured distributed database containing blocks of transactions.

p0115 The platform possesses two distinguishing characteristics allowing it to provide a decentralized system: security and global consensus. The latter is provided by the fact that everyone in the network is constantly validating and updating the state of the system collectively. Since each block in the chain is linked to the previous one, all users can verify if contents have not been modified. Keys are function of both the encrypted contents of the block and the previous block's key, thus involve a puzzle to be solved requiring computational effort. Keys are generated by miners: users providing the distributed computational effort and rewarded accordingly. The platform's decentralized nature makes it immune to many cyberattacks, even if a large number of users are targeted.

p0120 With the conception of Ethereum in 2012 and its launch in 2015, Blockchain 2.0 introduced smart contracts: digitally written and signed awaiting satisfaction of certain conditions to come into effect [27]. Ethereum's Blockchain 2.0 with its smart contracts was an equally massive success, amassing a market capital of over 1 Billion USD within less than a year of its launch, which exponentially grow to steadily remain above 10 Billion USD since 2017 (Fig. 2).



f0015 **FIG. 2** The phenomenal success of blockchain technology is shown by the number of daily transactions taking place on Bitcoin and Ethereum, currently the world's two largest cryptocurrencies.

p0125 With hundreds of billions of market capital, blockchain-based trading platforms have clearly gained society's trust, which became impossible to miss. Official recognition of cryptocurrencies and their underlying technology was inevitable. In 2012, the European Central Bank first recognized digital currencies [28] and later in 2015 just before Ethereum was about to be launched, a follow-up report was released with an extensive analysis of the success of their decentralized platforms [29]. This consolidated the acknowledgement of blockchain-based systems. During the past 2 years (between June 2017 and June 2019), there has been an average of more than 250,000 daily Bitcoin transactions, and more than 600,000 Ethereum daily transactions. Bitcoin and Ethereum continue to dominate as the two leading digital currencies with market capitals well above 10 and 100 Billion USD since 2017, respectively. However, there are numerous other blockchain-based cryptocurrencies which have emerged, with hundreds of thousands of daily transactions

p0130 The massive success and recognition of blockchain with its smart contracts as a decentralized commercial system has led many people to investigate the application in different sectors, particularly those that are shifting most toward a decentralized structures. The secure cryptographic algorithm of blockchain and its immunity to many cyberattacks is even more reason why it is currently seen as an enabling technology as it may potentially offer a solution to many data security/privacy problems caused by IoT enabling.

s0030 2. Adoption of blockchain by the energy sector

p0135 Around the same time when blockchain-based commercial platforms were rising and gaining global recognition, the energy sector was going through a massive transformation of its own. Motivated by a triad of causes (security of supply, environmental protection, and economic efficiency), legislation was being passed worldwide eagerly promoting demand-side management (DSM) strategies, specifically demand response (DR) programs. DR inherently relies on the availability of two main things: distributed energy resources (DERs) and SG infrastructure (with smart metering and communication devices). In 2012, the EU passed a directive to direct the rollout of SGs to implement DR programs (and multiple similar legislation was passed worldwide contemporarily) [30]. This ultimately meant that power and energy systems were about to rapidly witness two major transformations: physical decentralization due to DER installations and information decentralization due to smart metering and SG rollout.

p0140 It is important to elaborate that decentralization can occur at three different and distinguishable layers:

u0030 ***Decentralization of power systems***: This is related to the physical disaggregation of power generation, for example, DERs.

u0035 ***Decentralization of information systems***: Due to interconnection of even the smallest devices as in the IoT paradigm.

u0040 ***Decentralization of energy markets***: Is the case with P2P trading of generated energy by prosumers.

p0165 An advantage of decentralized systems is their capacity to make better use of the local endogenous resources and reduce costs and losses of transporting these resources, consequently leading to more environmental sustainability. Economic sustainability depends on the scale factor; big centralized systems are more efficient with low unitary costs. Small decentralized systems are less efficient with high unitary costs. However, recent technological developments of decentralized systems are enabling them to be economically competitive with their centralized counterparts. The three levels of decentralization are interinfluential and complementary.

Q0015 *Between P2P energy trading and IoE there is a clear emergence of what is referred to as* ***democratic energy systems*** *in which fundamental aspects are (1) significant citizen participation and (2) decentralized decision making in operation, management, planning, and trading, and (3) RES-dominated generation.*

s0035 2.1 P2P energy markets: The emerging paradigm shift

p0170 Conventional electrical power systems had unidirectional energy flow from generation to consumption. A centralized structure was best suited for this model with different utilities managing operation, planning, and energy market operations. Increased penetration of prosumers with DERs made electric power systems more decentralized and rendering the conventional model obsolete. First, energy was now being generated at both ends of the conventional chain and therefore roles of operators and utilities need to be redefined or the structure shuffled altogether. Second, DERs are increasingly incorporated into energy networks without being given any operational role or access to the wholesale market which is not sustainable [31].

p0175 In the beginning, feed-in-tariffs were offered with the intention of incentivizing small consumers to install small renewable energy generation (e.g., rooftop solar PV). Consumers generating electricity with renewable sources would be able to feed any surplus energy into the grid and are paid for it, albeit at a rate which is significantly lower than the electricity market price. This among other reasons started creating distrust between large utilities and system operators on one hand and DER owners on the other. With the decreasing price of renewable installations and the ease of acquiring them, small prosumers start looking for alternatives of trading electricity which can eliminate need for a middle man such as P2P trading.

p0180 After witnessing its capability to provide fully decentralized commercial trading platforms, it was clear that blockchain offered the ideal solution for newly emerged prosumers and their desire for citizen-run democratic energy

B978-0-12-817862-1.00003-8, 00003

systems. Multiple successful tests of blockchain-based P2P platforms started being carried out, albeit on small scales. Prior to the launch of Ethereum's Blockchain 2.0 and smart contracts in 2015, the role of blockchain was limited to enabling a secure and reliable distributed ledger of transactions, and thereby the early experiment with blockchain in P2P energy trading were strictly limited to its use to record financial transactions.

p0185 2012 was an important year in the transition to blockchain-based applications in the energy sector. The EU directive for SG rollout was approved, incentivizing researchers and stakeholders to seek new innovative data models and manage these new smart interconnected microgrids with DERs [30]. The first academic article putting forth the concept of "transactive energy" was published in 2013, proposing a vision of decentralized and self-sustaining microgrids capable of autonomous transactive operation [32].

p0190 This sparked a new trend in academic research, attempting and designing solutions based on this transactive energy vision. It is important to recall that at the time of the first transactive energy publication (early 2013), only first generation blockchain platforms have been in operation. Without smart contracts, and being limited only to financial transactions, the potential of blockchain being a suitable enabler for such a system was extremely limited. Thus, in the early years of research on transactive energy, blockchain was seldom mentioned.

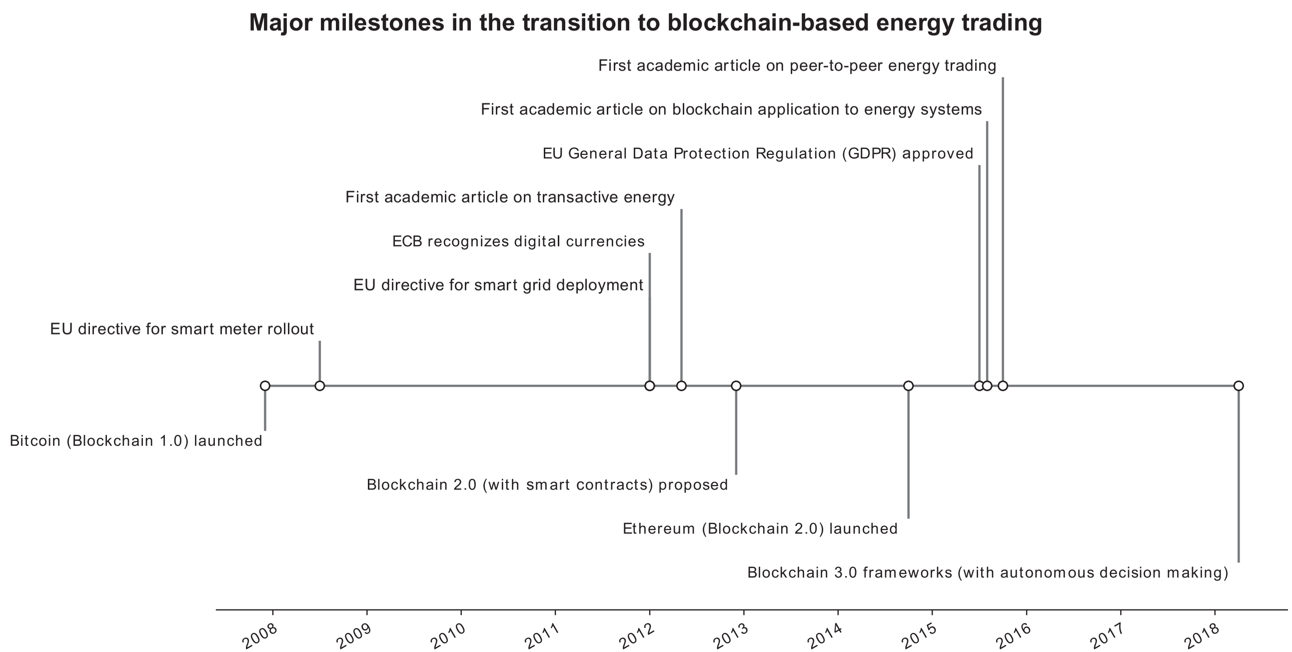
p0195 With the proposal of Blockchain 2.0 in late 2012 and the launch of Ethereum in late 2015, successfully incorporating smart contracts, this second generation of blockchain technology was suitable to provide for the needs of the energy sector. Smart contracts made energy trading possible in the way that was being envisioned by researchers on transactive energy networks. Therefore, a few months after the successful launch of Ethereum and the witness of its success, the first academic research papers proposing a validated methodology for blockchain applications to energy systems and peer-to-peer electricity trading were made toward the end of 2015 and the beginning of 2016 (Fig. 3) [33–35].

s0040 2.2 Expansion of blockchain applications

p0200 Once the first proposals were presented for the application of blockchain in the energy sector, its expansion became exponential. In 2016, recognition of blockchain as an inevitable enabler of future energy grids and markets became obvious around the world. The major reports were published in 2016 by global consultancy firms and governmental agencies which investigated the status-quo of blockchain applications at the time and predicated its great potential in the years to come.

p0205 PricewaterhouseCoopers (PwC) released a report [36] in highlighting the opportunities blockchain offers for energy producers and consumers. The report started by stating that blockchain's transaction model which shifts from centralized structures to P2P can reduce costs and speed up processes resulting in more

Shafie-khah, 978-0-12-817862-1



f0020 **FIG. 3** Timeline of major milestones and milestones taking place in the transition toward blockchain-based energy trading.

B978-0-12-817862-1.00003-8, 00003

flexible systems. The report highlights that while some level of maturity is being reached in the financial sector, the technology is still being developed for other applications with some barriers in the way, primarily conflict resolution and legal and regulatory requirements for fully decentralized systems. The Brooklyn Microgrid project was a successful experiment in which a microgrid consisting of a group of 10 households directly traded surplus solar energy generated using a blockchain system. Smart meters were used in conjunction with blockchain's smart contracts to keep track of energy produced and to automatically effect transactions, respectively. An energy token system was used for energy payments. Most start-ups working on blockchain applications at the time were developing cryptocurrencies specific for energy trading. The report emphasized the opportunity blockchain offers for prosumers of electricity in a P2P system, by providing more flexible and autonomous systems. In addition, the report highlights that blockchain could potentially be employed to a wide range of uses other than energy transactions, which include documentation of ownership (of energy generated), guarantees of origin, renewable energy certificates, and others. While blockchain could radically transform the energy sector, the report stated that current legal and regulatory frameworks need to be adjusted to cope with large-scale decentralized transactions models to be made possible.

p0210 The German Energy Agency (dena) conducted a survey [37] among 70 decision makers in the German energy industry regarding blockchain applications; 69% said they had already heard of existing blockchain applications in the energy sector and 52% either have blockchain implementations or ongoing plans thereof; 81% of the respondents are confident that blockchain will likely have a significant influence on the industry. Potential use cases that they envision were (in decreasing order of potential): security, decentralized generation, P2P trading, mobility, metering and data transfer, trading platforms, automation, billing, grid management, and communication. Blockchain's potential in cost reduction and as an enabler for new business models was reported. Since it was expected to be more disruptive compare to current technological alternatives, it had a higher chance of being the dominant design in applications where P2P trading has not yet been established on a large scale. Despite changing the structure of energy trading, if blockchain applications prove to have monetary or timely advantages over existing solutions, the critical number of market participants would be convinced to abandon current platforms in favor of blockchain. Rapid successful launching of prototypes around the world might make Germany and the EU lagging behind globally with current regulator frameworks being completely unsuitable and uncompliant with blockchain applications. Thus, they urged policymakers to consider it as a top priority.

p0215 Another report [38] studied the development of blockchain use cases by assuming the role of R&D developers. First, global consensus was identified as the primary disruptive element of blockchain technology in the energy sector.

This makes it an enabler technology for platforms with fully decentralized control which is particularly useful in situations where transacting parties lack trust. In addition, blockchain offers more efficient structures by removing the need for data to be synchronized with and by an intermediary, which is particularly useful in industry-level applications. For global and cross-country applications, the main potential of blockchain technology lied in its ability to offer interoperability between devices and systems. As such, the report identified that interoperability and flexibility is the target state which blockchain development in the energy sector must aim for. A conceptual use case which involved using blockchain in conjunction with smart meters was made and evaluated with industry specialists. The report recommended that being a disruptive technology to the energy sector, companies planning on developing blockchain energy applications should build strategic understanding of use cases in collaboration with blockchain technology developers by insourcing the knowledge.

p0220 An article [35] published in 2016 modeled and simulated a case of P2P energy trading in an SG. The proposed model was a fully decentralized private trading platform based on blockchain with multisignatures and anonymous encrypted message propagation streams. The system was resistant against significant common cyberattacks. In addition, the privacy of trading parties was found to be well protected by the system. By comparison with the results with a simulated centralized system, it concluded that the proposed system is a feasible application of blockchain technology to develop secure and efficient fully decentralized energy trading platforms.

p0225 A whitepaper [39] published by ParisTech in 2016 investigated new models for managing distribution grids. They proposed creating virtual distribution grids as a layer above the physical one. A blockchain-based platform would be used for transactions of surplus energy from homes in a distributed architecture. The proposed model was neither implemented nor tested. However, the paper attempted to provide blockchain usage model in the energy industry which is compatible with the current market structures. A journal [40] published in 2017 studied the energy market in Perth, Australia, where a recent successful experiment with a blockchain-trading platform was performed (similar Brooklyn). It showed that proliferation of cheap renewable generation and battery storage technologies are going to soon result in a paradigm shift in the energy industry to what they referred to as “citizen utilities.” The paper states that an inevitable shift to distribute and bidirectional energy systems and more decentralized energy markets will take place, where blockchain will be the basis of transactions such systems. The response of traditional market players would be what the paper called a “fight, flight, or innovate” one: fight will be the case if markets are resistant and in denial of the new paradigm shift; flight is if energy utilities take no action and possibly divesting investment in traditional markets; and innovate is if current utilities embrace the new technologies driving the paradigm shift.

B978-0-12-817862-1.00003-8, 00003

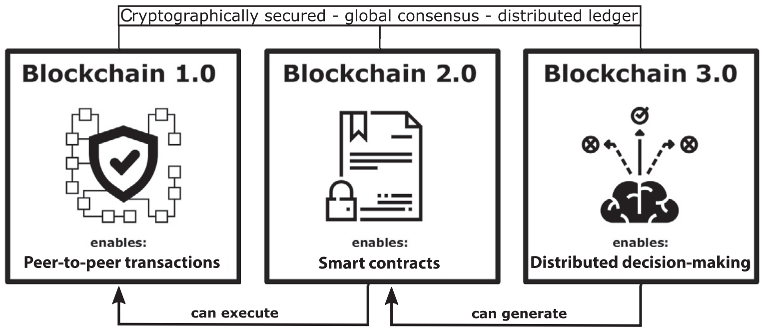
This chapter concludes that there is a rapid change to a new energy market model which is operated not by utilities, but by consumers and that this should be facilitated in what the author called "democratization of power."

s0045 3. Blockchain 3.0: Next-generation energy systems

p0230 Up to this stage, all published works and conducted experiments considered the capabilities of Blockchain 2.0. The cryptographically secured, consensus-based, approach enabled the elimination of financial mediators. Similarly, smart contracts enabled a fully decentralized market were energy can be traded. However, there was still a major pillar missing from the IoE vision for a fully autonomous transactive energy network. As mentioned earlier, there are three distinguishable layers of energy systems: the grid, the markets, and the information infrastructure. While Blockchain 2.0 solutions provided a way of managing the latter two in a fully decentralized fashion, it was not sufficient to be applied on the first. Operation and control of power systems require the solution of complex optimization and forecasting models, and it was still extremely challenging at that stage to develop a fully decentralized operation or control framework for electrical grids which would justify the dispensability of a (central) grid operator.

p0235 Only one academic paper at the time was proposed a blockchain-based solution for distributed optimization and control of electric grids in a P2P market architecture [41]. A decentralized optimal power flow (OPF) model for scheduling DERs on a microgrid was built and tested. Distributed optimization (namely ADMM) was used to decompose the OPF problem making it compatible with blockchain architecture. The cost function was decomposed into a set of local functions, and a global function which is a function of the local ones. In this manner, the scheduling and dispatch routine could be performed in a fully decentralized fashion using blockchain and smart contracts. The model was tested on a 55-bus microgrid with a dispatchable central generator, uncontrolled plug loads, nondispatchable renewable energy sources, shapeable loads, deferrable loads, and batteries. A day-ahead scheduling problem was considered with 1-h intervals. Blockchain and smart contracts used to perform optimization and control actions, and clearing prices, recording energy consumption (smart meters), and billing contracts (payment, charges, and penalties). The optimal cost based on ADMM was 0.4% larger than the centralized one. Shorter time horizons, ancillary services, or stochastic behavior were not considered. The aim was providing proof of the feasibility of using blockchain for distributed optimization and control grid applications. The success was due to the combination of Blockchain 2.0 and ADMM and set the standard for future studies which attempted to develop the next generation of blockchain which allowed not only for decentralized financial and information transactions, but also for autonomous operation of power systems.

B978-0-12-817862-1.00003-8, 00003



f0025 **FIG. 4** Timeline of major milestones and milestones taking place in the transition toward blockchain-based energy trading. *(Icons licensed as CCBY: Blockchain by Maria Kislitsina, smart contract by Anatolii Babii, and decision making by Chanut is Industries from the Noun Project.)*

p0240 This set the stage for the development of what came to be known as Blockchain 3.0 platforms. The evolution of blockchain (Fig. 4) can thus be summarized as follows:

u0045 • **Blockchain 1.0**: A fully distributed ledger of transactions which are cryptographically secured and rely on global consensus.

u0050 • **Blockchain 2.0**: Includes smart contracts which digitally written and signed awaiting satisfaction of certain conditions to come into effect, executing peer-to-peer transactions.

u0055 • **Blockchain 3.0**: A fully decentralized platform capable of autonomous operation relying on distributed mathematical models. This self-managing system can determine optimal strategies to ensure global benefit, and thereby constructing smart contracts accordingly.

p0260 In this book, different blockchain-based solutions for the management of SGs are presented, ranging from trading markets to complex operational problems such as DR implementation and grid control. Thereby, all the solutions presented in this book are the state of the art in blockchain-based energy systems, being Blockchain 3.0 solutions. The ultimate objective of employing Blockchain 3.0 is to achieve the ideal structure of an IoE transactive energy network, possessing fully autonomous and fully decentralized operation, aiming at the benefit of end users first and foremost.

ac0010 Acknowledgments

p9000 M. Lotfi acknowledges the support of the MIT Portugal Program (in Sustainable Energy Systems) by Portuguese funds through FCT, under grant PD/BD/142810/2018. J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under POCI-01-0145-FEDER-029803 (02/SAICT/2017).

References

[1] P.S. Antón, R. Silberglitt, J. Schneider, The global technology revolution: bio/nano/materials trends and their synergies with information technology by 2015, Tech. Rep. National Defense Research Institute, 2015, http://www.rand.org/.

[2] M. Hermann, T. Pentek, B. Otto, Design principles for Industrie 4.0 scenarios, in: Proceedings of the Annual Hawaii International Conference on System Sciences, vol. 2016-March, 2016, pp. 3928–3937, https://doi.org/10.1109/HICSS.2016.488.

[3] K. Schwab, The fourth industrial revolution: what it means and how to respond, World Economic Forum (2016), https://doi.org/10.1038/nnano.2015.286.

[4] L. Elliott, Fourth industrial revolution brings promise and peril for humanity, The Guardian (2016), http://www.theguardian.com/business/economics-blog/2016/jan/24/4th-industrial-revolution-brings-promise-and-peril-for-humanity-technology-davos.

[5] International Telecommunication Union, The Internet of Things, Tech. Rep., International Telecommunication Union, 2005, https://doi.org/10.1109/IEEESTD.2007.373646.

[6] A. Nordrum, Popular Internet of Things forecast of 50 billion devices by 2020 is outdated, in: IEEE Spectrum, 2016.

[7] Gartner, Gartner says 6.4 billion connected "Things" will be in use in 2016, Up 30 percent from 2015 [press release], Tech. Rep., Gartner, Inc., Barcelona, 2015, http://www.gartner.com/newsroom/id/3165317.

[8] Ericsson, Ericsson mobility report: on the pulse of the networked society, Tech. Rep., Ericsson, 2016, https://doi.org/10.3103/S0005105510050031.

[9] S. Lucero, IoT platforms: enabling the Internet of Things, in: IHS Technology, 2016, https://cdn.ihs.com/www/pdf/enabling-IOT.pdf.

[10] C. MacGillivray, M. Torchia, M. Cinco, M. Kalal, M. Kumar, R. Membrila, A. Siviero, Y. Torisu, N. Wallis, Worldwide Internet of Things forecast update, 2016–2020, IDC Market Forecast (2017) 40755516, http://www.idc.com/getdoc.jsp?containerId=US40755516.

[11] Dimensional Research, ParStream, Internet of Things (IoT) meets big data and analytics: a survey of IoT stakeholders, Tech. Rep., 2015 (march).

[12] A. Meola, The roles of cloud computing and fog computing in the Internet of Things revolution, in: Business Insider, 2016.

[13] IBM, What is cloud computing?, 2017, https://www.ibm.com/cloud-computing/learn-more/what-is-cloud-computing/.

[14] Gartner, Gartner says worldwide IoT security spending to reach $348 million in 2016 [press release], Tech. Rep., Gartner, Inc., 2016, http://www.gartner.com/newsroom/id/3291817.

[15] European Parliament and of the Council of 27 April 2016, Regulation (EU) 2016/679, 2016, https://eur-lex.europa.eu/eli/reg/2016/679/oj.

[16] A. Jung, Smart Grid 2.0 Building the Internet of Energy Supply, Spiegel Online, 2010, pp. 1–3.

[17] A.S. Sani, D. Yuan, J. Jin, L. Gao, S. Yu, Z.Y. Dong, Cyber security framework for Internet of Things-based energy internet, Future Gener. Comput. Syst. (2018), https://doi.org/10.1016/j.future.2018.01.029.

[18] C.C. Lin, D.J. Deng, W.Y. Liu, L. Chen, Peak load shifting in the internet of energy with energy trading among end-users, IEEE Access 5 (2017) 1967–1976, https://doi.org/10.1109/ACCESS.2017.2668143.

[19] Q. Sun, R. Han, H. Zhang, J. Zhou, J.M. Guerrero, A multi-agent-based consensus algorithm for distributed coordinated control of distributed generators in the energy internet, IEEE Trans. Smart Grid 6 (6) (2015) 1–14, https://doi.org/10.1109/TSG.2015.2412779.

[20] N. Bui, A.P. Castellani, P. Casari, M. Zorzi, The internet of energy: a web-enabled smart grid system, IEEE Netw. 26 (4) (2012) 39–45, https://doi.org/10.1109/MNET.2012.6246751.

[21] A. Jindal, N. Kumar, M. Singh, A unified framework for big data acquisition, storage and analytics for demand response management in smart cities, Future Gener. Comput. Syst. (2018), https://doi.org/10.1016/j.future.2018.02.039.

[22] M. Jaradat, M. Jarrah, A. Bousselham, Y. Jararweh, M. Al-Ayyoub, The internet of energy: smart sensor networks and big data management for smart grid, Procedia Comput. Sci. 56 (1) (2015) 592–597, https://doi.org/10.1016/j.procs.2015.07.250.

[23] K. Wang, J. Yu, Y. Yu, Y. Qian, D. Zeng, S. Guo, Y. Xiang, J. Wu, A survey on energy internet: architecture, approach, and emerging technologies, IEEE Syst. J. (2017) 1–14, https://doi.org/10.1109/JSYST.2016.2639820.

[24] P. Tenti, T. Caldognetto, Optimal control of local area energy networks (E-LAN), Sustain. Energy Grids Netw. 14 (2018) 12–24, https://doi.org/10.1016/j.segan.2018.03.002.

[25] J. Cao, M. Yang, Energy internet—towards Smart Grid 2.0, in: Proceedings of the International Conference on Networking and Distributed Computing, ICNDC, 2014, pp. 105–110, https://doi.org/10.1109/ICNDC.2013.10.

[26] S. Nakamoto, Bitcoin: A Peer-to-Peer Electronic Cash System, 2008, https://doi.org/10.1007/s10838-008-9062-0.

[27] M. Swan, Blockchain: Blueprint for a New Economy, O'Reilly Media, Inc., 2015, https://doi.org/10.1017/CBO9781107415324.004

[28] European Central Bank, Virtual currency schemes, Tech. Rep., 2012, http://www.ecb.europa.eu.

[29] European Central Bank, Virtual currency schemes—a further analysis, Tech. Rep., European Central Bank, 2015, https://doi.org/10.2866/662172.

[30] M. Lotfi, C. Monteiro, M. Shafie-Khah, J.P.S. Catalao, Evolution of demand response: a historical analysis of legislation and research trends, in: 2018 Twentieth International Middle East Power Systems Conference (MEPCON), December, IEEE, 2018, pp. 968–973, https://doi.org/10.1109/MEPCON.2018.8635264.

[31] Electric Power Research Institute, The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources, EPRI, 2014.

[32] W. Cox, T. Considine, Structured energy: microgrids and autonomous transactive operation, in: 2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT), February, IEEE, 2013, pp. 1–6, https://doi.org/10.1109/ISGT.2013.6497919.

[33] W. Inam, D. Strawser, K.K. Afridi, R.J. Ram, D.J. Perreault, Architecture and system analysis of microgrids with peer-to-peer electricity sharing to create a marketplace which enables energy access, in: 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), June, 2015, pp. 464–469, https://doi.org/10.1109/ICPE.2015.7167826.

[34] M. Pustišek, A. Kos, U. Sedlar, Blockchain based autonomous selection of electric vehicle charging station, in: 2016 International Conference on Identification, Information and Knowledge in the Internet of Things (IIKI), October, 2016, pp. 217–222, https://doi.org/10.1109/IIKI.2016.60.

[35] N.Z. Aitzhan, D. Svetinovic, Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams, IEEE Trans. Depend. Secure Comput. 15 (5) (2018) 840–852, https://doi.org/10.1109/TDSC.2016.2616861.

[36] PwC, Blockchain—an opportunity for energy producers and consumers? Tech. Rep., PwC, 2016, http://www.pwc.com/gx/en/industries/energy-utilities-mining/power-utilities/publications/opportunity-for-energy-producers.html.

[37] German Energy Agency, Blockchain in the energy transition. A survey among decision-makers in the German energy industry, Tech. Rep., German Energy Agency, Berlin, 2016.

[38] J. Mattila, T. Seppälä, C. Naucler, R. Stahl, M. Tikkanen, A. Bådenlid, J. Seppälä, Industrial blockchain platforms: an exercise in use case development in the energy industry, Tech. Rep., The Research Institute of the Finnish Economy (ETLA), 2016, https://doi.org/10.1017/CBO9781107415324.004.

[39] J. Horta, D. Kofman, D. Menga, Novel paradigms for advanced distribution grid energy management, ArXiv, 2017, abs/1712.05841.

[40] J. Green, P. Newman, Citizen utilities: the emerging power paradigm, Energy Policy 105 (2017) 283–293, https://doi.org/10.1016/j.enpol.2017.02.004.

[41] E. Munsing, J. Mather, S. Moura, Blockchains for decentralized optimization of energy resources in microgrid networks, in: 2017 IEEE Conference on Control Technology and Applications (CCTA), 2017, pp. 2164–2171, https://doi.org/10.1109/CCTA.2017.8062773.