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Electricity powered by blockchain: A review with a European perspective

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HIGHLIGHTS

- Many blockchain projects in Europe's energy systems fail.
- Technological, legal, and organizational challenges often outweigh benefits.
- Certificate trading and machine identities are increasingly hyped applications.
- Blockchain can best leverage its benefits when it takes a backseat.

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ABSTRACT

Blockchain is no longer just a hype technology, and effective blockchain applications exist in many industries. Yet, few blockchain projects have been successful in Europe's energy systems. To identify the reasons for this slow progress, we reviewed the recent energy literature regarding the use of blockchain, analyzed industry reports, and interviewed experts who have conducted blockchain projects in Europe's energy systems. Our analysis reveals eight common use cases, their expected benefits, and the challenges encountered. We find that the expected benefits are often little more than generic hopes, largely outweighed by technological, organizational, and regulatory challenges. The identified challenges are significant and numerous, especially for peer-to-peer trading and microgrid use cases. The fact that few projects have yet provided robust evidence for profitable use suggests there is still a rocky road ahead. Moreover, many use cases appear to require more than just blockchain technology to succeed. In particular, privacy and scalability requirements often call for systems in which blockchains only take a backseat. This realization may be essential for the future use of blockchain technology in energy systems – in Europe and beyond.

1. Introduction

In the past few years, blockchain has attracted attention across many industries and become a veritable hype technology. In a predominantly technology-driven effort, various industries have initiated projects to test the prospects and limitations of blockchain applications. Success stories – such as some reported from logistics and retail, where blockchain enables the sharing of digital trade documents and improves the efficiency of supply chains [1,2] – have fueled similar expectations for the use of blockchain in energy systems [3,4]. In particular, blockchain's ability to enable intermediary-free transactions was expected to support the integration of an increasing number of distributed renewable energy sources (RES) that require more flexible, local concepts [5–7]. Accordingly, various research and pilot projects began to explore use cases for blockchain [5,8]. Many of these projects were concentrated in Europe, which could be considered a hotbed for the use of blockchain in energy systems [5,9].

Blockchains are primarily known for their use as registries for cryptocurrency transactions, such as Bitcoin or Ethereum, and for the enormous energy consumption of the Proof of Work (PoW) consensus mechanisms many of these cryptocurrencies use [10–12]. At the same time, blockchains have gained a reputation of being particularly secure and tamper-proof database systems. Every transaction written to a blockchain is cryptographically linked to the previous transaction,

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which creates a transparent and traceable record. Copies of this record are stored across various nodes in a blockchain network and authorized nodes continuously vet the validity of new transactions [5,12].

These origins and properties have made blockchain especially popular in the context of peer-to-peer concepts. The proposed use cases range from transaction processing at the retail level to supporting selected processes in wholesale and system services markets [13–15]. Blockchain was hyped for improving the balancing of generation and demand, and for facilitating more automated and secure transactions between the various actors [13,16,17]. Similar expectations emerged in the context of e-roaming. Blockchain was promoted as a means to mediate range anxiety by facilitating vehicle-to-vehicle transactions [16] or prosumer services [5,15]. More recent ideas include the labeling of electricity [16,17], the trading of certificates of origin or emission [18,19], and machine identities [20,21].

Despite this wide range of use case ideas, many projects have since been abandoned or are still at a pilot stage – especially in Europe [5,9]. Some publications, such as [5,14,22], have begun to identify challenges that might contribute to this slow adoption. These encompass, for instance, high barriers to market entry for smaller actors [5], legally required market actor roles [6], and scalability and interoperability issues [14,23]. Yet, it remains ambiguous how exactly these challenges impact the feasibility of the various blockchain use cases and what implications they may have for the future of blockchain technology in Europe's energy systems.

Thus, the aim of our paper is to provide a balanced, more practice-informed, and 'past-the-hype' overview on the use of blockchain technology in Europe's energy systems. Secondly, we aim to identify and rate the benefits and challenges related to the use of blockchain. Thirdly, we indicate avenues for further research where the use of blockchain appears promising. To inform our investigation, we reviewed academic papers, and in addition, studied industry reports and conducted expert interviews. From this consolidated analysis, we identified eight common use cases, their expected benefits, and the challenges encountered.

2. Background

Blockchain technology has its roots in the cryptocurrency industry [24], but over the last years it has also found its way into energy systems [6,22,25]. Simply speaking, blockchains are a particular type of database that groups data into a block structure [25,26]. More technically speaking, blockchains are distributed ledgers that are replicated, shared, and distributed across multiple servers in a blockchain network – so-called nodes [19,27]. A selection of these nodes can append new blocks using so-called consensus mechanisms that help select the node that can append the next block [19,26,28]. Each new block references the previous block using a hash-pointer [29]. These pointers typically make retrospective changes to the blockchain easy to detect, and together with data replication on several nodes, they create a highly secure, transparent, auditable, and robust transaction environment [30].

Dependent on the network design, any participant can host a blockchain node and add a new block [31]. Such a 'public', permissionless design is particularly attractive for residential peer-to-peer trading, as it permits any prosumer to participate [8]. Yet, there are also 'private', permissioned designs that limit participation, e.g., to certain companies or public organizations [32]. These designs are closer to the structure of many European energy systems and allow for the distribution of rights to write and access data on the blockchain in accordance with legally mandated roles and attributed competencies [5,6].

Beyond storing data and processing simple payments, blockchains may also execute programming logic with the help of so-called smart contracts [33,34]. These are redundantly executed scripts that enable participants to control how data is processed by the blockchain network. As such, they can considerably reduce dependencies on trusted third parties and enable reliable information sharing and process automation [35–37]. Moreover, they reduce the vulnerability to failures and attacks, which makes blockchain particularly attractive for applications in energy systems [38,39]. The avoidance of trusted third parties also prevents the aggregation of market power and mitigates lock-in effects [40].

Inspired by the technological capabilities of blockchains and their use across various industries, academic researchers have started to explore their potential benefits for energy systems. This research has quickly evolved into a plethora of different and often parallel discussions [26,34,35], ranging from conceptual aspects to empirical and analytical models [25,36]. Examples include prototypes with more accurate pricing mechanisms for peer-to-peer markets [39,40] and calculations of costs (reductions) [41,42]. While some studies try to capture benefits over the full range of possible applications [5], others focus on the 'disruptive potential' of the use of blockchain [35]. A prominent example for these 'disruptive' use cases is residential peer-to-peer trading [5,14,21]. Overall, discussions on the use of blockchain in energy systems are mostly theoretical and strongly focused on potential benefits [25,26].

Previous reviews also only selectively elaborate on the challenges of using blockchain technology in energy systems. One of the first reviews by Andoni et al. [5] aims to provide a comprehensive overview of technical aspects, such as different consensus mechanisms, and explores their application in 140 blockchain research and pilot projects. Based on their analysis of academic literature and project reports at the peak of the blockchain hype, they derive potential opportunities and challenges of blockchain technologies in diverse use cases. Another review by Ante et al. [22], past the initial hype, uses a bibliometric analysis to explore dominant research streams on the use of blockchain in energy systems. They identify overall six use case patterns and explore the extent to which the use cases focus on blockchain or on general improvements of the energy system without a specific technology. Based on the analysis of selected papers, Ante et al. [22] also discuss a roadmap for future research. The latest review by Choobineh et al. [14] aims to provide a more comprehensive overview of benefits and challenges of using blockchains in energy systems. Based on a literature review, they derive a plethora of vague benefits based on inherent characteristics of blockchain technology, five dominant challenges of blockchain applications in energy systems, and four emerging trends that may help blockchain thrive.

Although instructive, these reviews provide few indications of feasible applications, their actual benefits, or challenges associated with the use of blockchain technology. Moreover, they do not include 'past-the-hype' insights from pilot projects that might advance the understanding of drivers and inhibitors of blockchain applications in energy systems.

3. Materials and Methods

Here, we offer a balanced and empirically substantiated overview of common blockchain use cases in Europe, including the benefits and challenges of using blockchain technology. We selected three different data sources for our analysis: Academic literature, industry reports, and expert interviews. First, we searched for high-quality academic literature by conducting a systematic literature review. For our review, we followed Kitchenham's five-step approach [43], which involved (1) the identification of relevant publications, (2) their selection, (3) their quality assessment, (4) the extraction and evaluation of data, and (5) the aggregation and interpretation of data. Second, we identified industry reports from renowned agencies, research institutions, think tanks, start-ups, non-profit organizations, and consulting firms to add an industry perspective. Lastly, we conducted interviews with industry experts to gain in-depth insights into blockchain projects in Europe's energy systems. In total, we reviewed 89 academic papers, analyzed 42 industry reports, and conducted 45 interviews with academic, technical, legal, and business experts who have worked on blockchain projects in

Europe's energy systems.

3.1. Data collection

3.1.1. Academic literature selection

In line with Kitchenham's approach [43], we conducted a keyword search across five databases: IEEE Xplore, Scopus, Science Direct, Taylor & Francis, and SAGE Journals. To combine our keywords, we used the Boolean operators AND and OR:

1. "Blockchain" **AND** ("Energy Sector" **OR** "Energy System" **OR** "Power System" **OR** "Electric Power System")
2. "Blockchain" **AND** ("Power Markets" **OR** "Electricity Trading")
3. "Blockchain" **AND** ("Energy Management System" **OR** "Electricity Management System")

In addition, we applied a set of selection criteria regarding the year of publication, language, and publication type. That is, we focused on publications from 2018 onwards when blockchain projects in Europe's energy systems began to reach a level of maturity beyond conceptualization and proof of concepts. For additional quality assurance, we focused on published and peer-reviewed articles in journals with a 75 percentile or higher Scopus rating and only included articles written in English. To filter out academic contributions that did not focus on blockchain applications in energy systems, we restricted the search fields – dependent on the available filters for the different databases – to abstract, keywords, and introduction. All identified literature was transferred to the bibliographic manager Mendeley. We extracted overall 710 academic contributions with our initial keyword search after having removed duplicates.

We further refined the results of this pre-selection of relevant literature throughout Kitchenham's selection and quality assessment steps [43]. To illustrate these steps and our applied selection criteria, we used the Preferred Reporting Items for Systematic Reviews and meta-Analyses (PRISMA) protocol by [44]. The protocol afforded additional rigor and enabled transparency and replicability of our results (Fig. 1). During the screening and refinement phases, we reviewed titles and abstracts of the high-quality subset and narrowed down our body of literature to 89 academic publications that focused on the application of blockchain technology in energy systems (see Appendix A1).

3.1.2. Industry report selection

Industry reports were selected by identifying reports of renowned agencies, research institutions, think tanks, start-ups, non-profit organizations, and consulting firms from 2018 onwards. We only included reports that had a clear focus on the application of blockchain technology in energy systems. Regarding language, we primarily included reports that were either directly written in English or translated into English. After having reviewed the executive summaries and tables of content, we identified a total of 42 relevant industry reports, which are detailed in Appendix A2.

3.1.3. Interviews

Since literature and industry reports only provided a high-level overview of benefits and challenges in blockchain projects and often lacked a practice-informed perspective, our main method of data collection was interviews. More specifically, we contacted developers and employees of energy companies in key positions, who were directly involved in blockchain projects. Almost all interviewees were from Europe, where a large part of the ongoing blockchain projects in energy systems are located, such as Germany, Austria, Switzerland, and Spain. We conducted 45 semi-structured interviews using an interview guide (see Appendix A3) to ensure coverage of our focal topic while allowing the conversation to develop naturally [37,39]. This provided detailed and authentic insights into the interviewees' perspectives of their projects [40,41]. We conducted each interview with one or two interviewers, audio-recorded the discussion, and took notes. Audio recordings were later transcribed for further analysis.

The interviews consisted of overall three parts. We began with a brief introduction. We then asked the interviewees for their experience and perspective regarding the benefits and challenges of using blockchain technology in their project or related projects. Lastly, we asked for recommendations on how policy makers could contribute to the success of blockchain projects in energy systems. Dependent on the individual knowledge and expertise of our interviewees, we adapted the questions and changed the interviews' focus, allowing the interviewees to go into directions they found interesting [45]. We provide an overview of the interviews in Appendix A4.

3.2. Data analysis

From the identified academic literature, industry reports, and conducted interviews, we first extracted the most commonly discussed use cases. Those that were only mentioned in one or two studies, industry reports, or interviews, were excluded. This selection resulted in eight use cases, which we then analyzed regarding specific benefits and challenges of the use of blockchain technology. We based our review on a two-step coding process in line with Corbin and Strauss' [46] recommendations for grounded theory development. That is, we coded openly and focused on positively and negatively connotated statements regarding the implementation of blockchain technology for specific use cases. In a subsequent axial coding phase, we explored the relationship between different benefits and challenges and tried to find higher-level groups to summarize them. To support coding, we used the MAXQDA software toolkit. Our analysis led to overall 58 first-order themes and six second-order categories. More specifically, we identified three benefit and three challenge types: (1) efficiency benefits, (2) effectiveness gains, and (3) an added level of security as well as (1) organizational challenges, (2) technological challenges, and (3) regulatory challenges.

3.2.1. Use case analysis

To evaluate and rate the identified benefits and challenges for each use case, we employed established qualitative data analysis techniques

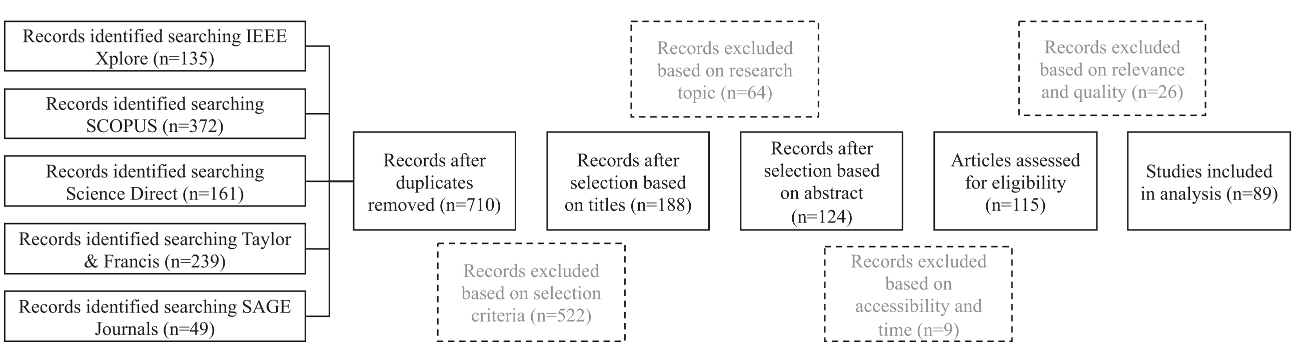

Fig. 1. Overview of the academic literature selection.

[47,48]. In particular, we went through three additional rounds of coding. In a first round, we read again through all data sources – that is, we challenged and validated our initial annotations of "benefit" or "challenge" for relevant statements allocated to specific use cases.

In the second round, we looked for adjectives, adverbs, or other details in the sentences surrounding the respective statements, such as elaboration on a specific benefit or challenge, to better assess their overall relevance for the success or failure of blockchain projects. As this proved difficult on a verbal basis, we transferred the extracted insights into a Likert-scaled format. Specifically, we used a 7-point Likert scale ranging from 1 (not substantial) to 7 (very substantial). To achieve objectivity, we collected the annotated statements in a large table that listed the identified use cases on the horizontal axis and the benefit and challenge types on the vertical axis.

In a third round of coding, we went through the collected statements and conducted an initial rating of the importance of individual benefits and challenges. Throughout this process, we used the above-mentioned criteria and coded in two independent two-person groups. These two groups would go through the aggregated statements and assign a numerical value within the 7-point Likert scale for each of the identified challenges and benefits of every use case. Thereafter, the two groups compared their independently obtained assessments, discussed differences, and settled on a final rating. Where the two groups differed significantly in their rating, we additionally consulted the interviewed experts. To evaluate the third round of coding, we calculated intra-rater and inter-rater reliability using the Cohen's kappa coefficient [49]. Scores of 0.90 and 0.72 for intra-rater and inter-rater reliability indicated a substantial to "almost perfect" overlap between the two groups [50].

To increase the clarity of our results, we summarized our rating in a heatmap (Fig. 2). More specifically, we used color-codes based on the 7-point Likert scale to signify the importance of an identified benefit or challenge category. We used green to signal substantial benefits (5–7) and negligible challenges (1–2), yellow for uncertain benefits (3–4) and manageable challenges (3–4), and red for negligible benefits (1–2) and substantial challenges (5–7). We provide a list of the sources on which we based our use case analysis in Appendix A5.

4. Results

4.1. Common use cases

Our analysis revealed that blockchain projects in Europe commonly focus on a set of eight use cases (Table 1).

4.1.1. Peer-to-peer electricity trading and decentralized system services

Many projects explore the use of blockchain for *retail* or *wholesale peer-to-peer electricity trading* as well as *decentralized system services*. These applications are similar in that each uses blockchain to reduce dependence on centralized market operators [25]. They differ, however, in the addressed market inefficiencies.

Retail trading applications seek to facilitate trading between small actors that typically do not have access to wholesale electricity markets. Specifically, they try to reduce the costs of small transactions by automating transaction processing with blockchain-based registries and smart contracts [40,41,51]. Reduced processing costs, in turn, would enable small electricity producers to turn a profit from selling their power [52–54]. Moreover, they would increase the attractiveness of buying local and thus create a larger pool of potential customers for small producers [5,55,56].

Most wholesale trading applications try to improve the operation of wholesale electricity markets. Specifically, they explore the use of blockchain-based registries and smart contracts to reduce the cost of clearing and settlement processes, for instance, by reducing the number

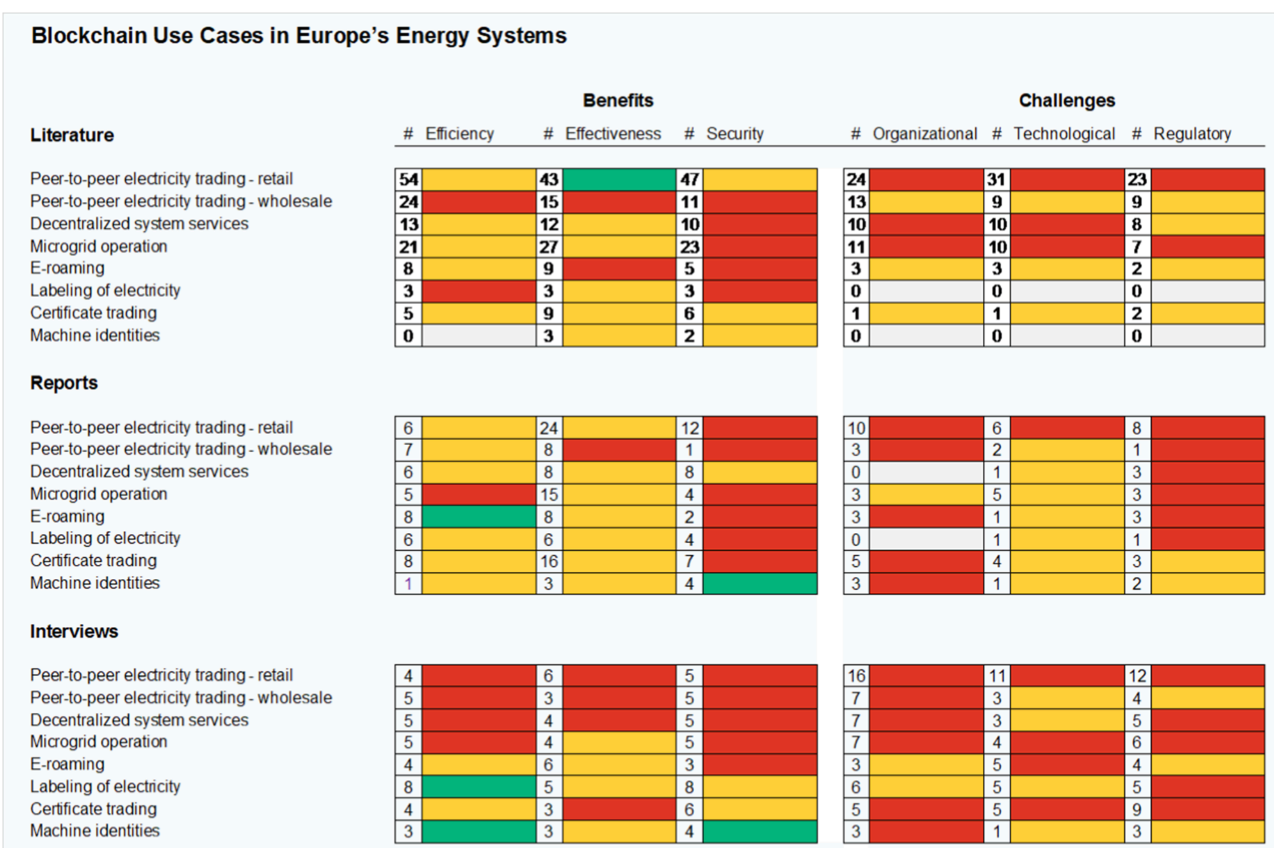

Fig. 2. Evaluation of commonly implemented blockchain use cases in Europe's energy systems.

Table 1
Identified, commonly discussed blockchain use cases in energy systems and their definitions.

Use Case	Use Case Definition
Peer-to-peer electricity trading – retail	Processing of transactions in (local) energy markets for small actors
Peer-to-peer electricity trading – wholesale	Processing of transactions in large commercial markets for electricity
Decentralized system services	Processing of transactions in markets for system services and flexibility
Microgrid operation	Balancing of demand and supply in microgrids as well as processing of related transactions
E-roaming	Exchange of financial and identity-related data between charging point operators, e-mobility service providers, and e-mobility customers
Labeling of electricity	Tracing of feed-in levels for power generation and storage facilities as well as processing of related energy purchase agreements
Certificate trading	Processing of clearing and settlement for certificates that provide proof of origin or emission from specific generation and storage facilities
Machine identities	Authentication and validation of identity-related documents that confirm identity attributes of e.g., power generation and storage units

of warranties required [35,57]. Moreover, smart contracts are discussed as means to automate certain exchange trading activities such as escrow services [35,58]. These improvements are expected to reduce access barriers to exchange trading so that also smaller actors can participate in these markets [3,59]. Some wholesale trading applications also focus on over-the-counter (OTC) electricity trading [6,60–62]. These applications try to reduce the use of e-mails, instant messaging, or phone calls in the processing of OTC transactions. They use blockchains as tamper-resistant registries to verify transactions in case of misunderstandings or suspected fraud [35,63].

Like wholesale applications, *decentralized system services* applications seek to improve the operation of system service markets. They explore the use of smart contracts to decentralize and automate many control services including registration, verification, and approval required for participation in these markets [61,64]. Smart contracts could additionally automate the activation and settlement of system services [35,40]. Moreover, they may optimize billing processes where these are characterized by cumbersome manual paperwork and require a substantial amount of time [25,65,66].

4.1.2. Microgrid operation

Microgrid operation applications provide automated microgrid management where conventional, centralized management models and tools are not feasible or desirable [67,68]. They involve the use of smart contracts to schedule and manage production and consumption units in microgrids [22]. Blockchain-based registries are used to collect and track schedules and flexibility potentials for these units. Smart contracts then use this information to balance demand and supply, automatically activate flexibility potentials when required, and even potentially increase cyber-security [69,70]. The unit's actual power generation and consumption levels are again tracked in a blockchain-based registry to facilitate later settlement and allocation of flexibility costs. Microgrid applications are typically combined with peer-to-peer trading applications to cover both grid management and economic aspects.

4.1.3. E-roaming

E-roaming applications address the problem of limited access to charging points by enabling the free and secure exchange of relevant data regardless of charging network membership [41,57,71]. Some of these applications rely on blockchains to exchange electric vehicle charging data and settle transactions between charging point operators and mobility service providers. Others use blockchains as a registries for identity-related documents that enable easy and secure identification and authentication of e-mobility customers. The blockchain attests the authenticity and validity of these documents. Smart contracts are used to validate the credentials and automatically issue invoices after the charging process has been completed.

4.1.4. Labeling of electricity

Labeling of electricity applications use blockchain to track the share of power being fed into the grid by different sources at the time of consumption [72]. These applications are typically combined with RES generation facilities to create 'green' labels and reduce the risks of greenwashing but some projects also focus on creating 'local' labels [73,74]. Smart contracts can additionally be used to automate the processing of energy purchase agreements for the labeled electricity. The settled quantities can again be stored on the blockchain [57,75,76] to mitigate concerns regarding the sources of consumed electricity, accelerate data exchange, and reduce manual processes [58,77].

4.1.5. Certificate trading

Certificate trading applications employ blockchain to create and exchange certificates that provide a proof of origin or emission [78]. They can be seen as an extension of labeling of electricity applications as most use labeling data to create certificates that establish the origin or emissions for specific generation and storage facilities [79,80]. The certificates can be anchored or fully stored on the blockchain to create a validity registry as well as a transparent and unequivocal ownership history [5,81,82]. Smart contracts are used for issuing as well as processing and documenting certificate exchange [83].

4.1.6. Machine identities

Several projects have recently begun to explore *machine identity* applications [57,84,85]. The underlying idea is to package identity-related information about power generation and storage units as machine-verifiable, digital credentials [86–88]. These digital credentials can then be used for identification and authentication purposes. They are typically anchored on a blockchain, which stores essential cryptographic material and information on accredited issuers, schemas to verify credential authenticity, and revocation registries to verify credential validity. Blockchains are used because certain blockchains readily support digital credentials and because they reduce lock-in effects [89,90].

4.2. Expected benefits

Results from our analyses of the eight use cases could be attributed to three types of expected benefits (Table 2): efficiency, effectiveness, and security. Use cases that emphasize efficiency use blockchain to improve the output of a process. For instance, this can involve the reduction of overhead costs associated with traditional trading practices, or an increased speed of transactions [3,91,92].

Use cases that pursue effectiveness aim to achieve a desired output by improving the structure of processes. Such improvement approaches primarily focus on the empowerment of small actors by excluding intermediaries, who process transactions, and on the design of

Table 2
Identified benefits of using blockchain in energy systems.

Efficiency	Effectiveness	Security
• Digitalization and automation of processes, services, and transactions • Reduction of process, service, and transaction costs • Flexibility of processes, services, and transactions	• Decentralization and disintermediation • Autonomy from macro-grids • Empowerment of small actors within energy communities • Market flexibility • Reduction of complexity	• Transparency • Data security and data sovereignty • Creation of trust through tamper-resistant data storage • Resiliency and reliability

decentralized and self-sustaining energy infrastructures [4,6,60]. Expected security improvements include the protection of processes from failure and attacks, ensuring reliable output. Specifically, blockchain technology is understood to enable tamper-resistant data storage [5,72,93] and strengthen cyber-security [3,92], which is believed to enhance the robustness of energy systems [34,92] and ensure the security of supply. Additional transparency provides monitoring capabilities, which further enhances security [52,94].

All benefits in our analysis fit into one of the three benefit types. Security benefits were commonly identified as being of secondary importance because acceptable levels of security are often already provided by common database technologies. Although we expected benefits to differ between the various use cases and project settings, most sources did not progress beyond the mention of generic benefits, and we could identify only few specific benefits (Table 2). In many ways, the named benefits were variations of general attributes of blockchain, such as secure and redundant data storage or reliable information sharing and process automation [5,19,22,72]. They appear more as hopes of a fundamental change to energy systems, not as real benefits derived from blockchain technology. For instance, the expected cost savings from the use of blockchain technology are difficult to quantify. Specifically, cost estimates for developing, maintaining, and integrating blockchain applications are often fraught with uncertainty and reference costs are hard to establish. As a result, few blockchain applications have a clear 'business case', which reduces their economic attractiveness.

4.3. Encountered challenges

In addition to benefits, we also identified challenges commonly encountered in blockchain projects (Table 3). The challenges are far more specific and numerous than the identified benefits. Although many challenges are particular to the respective use case, they can be grouped into three types: organizational, technological, and regulatory.

Organizational challenges include all problems arising from changes to organizational structures, roles, or processes. They result especially from the desired replacement of essential mediating actors and the vague delegation of responsibilities in decentralized and disintermediated structures [5,35,95]. Moreover, many actors are deterred by the need for high levels of involvement and participation combined with unpredictable and hidden costs, particularly when they feel little regulatory and customer pressure to innovate [60,96].

Technological challenges result from difficulties in integrating blockchain with legacy systems and meeting functional requirements for successful application in energy systems. A lack of interoperability and technical standards, and the blockchain trilemma of decentralization, scalability, and security [5,71,96] are particularly salient technological challenges. Moreover, throughput can be a challenge, especially for 'public' blockchains [97]. The academic literature also often discusses the high energy consumption of PoW based 'public' blockchains [78,98]. Yet, energy consumption is manageable for 'private' blockchains and also for 'public' blockchains when alternative consensus mechanisms are used [26,99].

Regulatory challenges refer to conflicts with rules regarding the organization and the responsibilities of actors in energy systems. Perceived regulatory barriers include privacy laws – such as the General Data Protection Regulation (GDPR) [100] – or energy market regulation [59]. While compliance with privacy laws appears more manageable for 'private' blockchains [100], substantial challenges remain, especially when competing organizations participate in the same private blockchain network. Furthermore, many energy market regulations presuppose a need to involve mediating actors, which makes such actors very difficult to replace [6,22,95,101]. The same applies to critical market actor roles, such as Transmission System or Distribution System Operators. These actors often have well-defined responsibilities, and their replacement may jeopardize the stability of energy systems. Legal uncertainties pertaining to alternative market actor roles, especially in *peer-to-peer electricity trading* applications, further exacerbate such concerns. Overall, the proposed deviations from current regulatory frameworks and legally required market roles make the use of blockchain in energy systems cumbersome.

Table 3
Identified challenges of using blockchain in energy systems.

Organisational	Technological	Regulatory
• Low market pressure and need for substantial investments • Low stakeholder acceptance and usability • Complex infrastructural and technological requirements to enable productive applications • Unpredictable and hidden costs • Unpredictable revenues • High organizational complexity of distributed market structures • Difficulties replacing critical, established, and mediating energy actors • Vague market actor responsibilities • Substantial efforts of automating and decentralizing governance • High involvement and participation effort • Difficulties maintaining social justice principles • Difficulties encouraging behavioral change of consumers	• Volatility of transaction speed • Lack of interoperability and technical standards • Blockchain trilemma of decentralization, scalability, and security • Complex and nontransparent data management • Few plug-and-play hardware and software components • Difficulties controlling data quality and quantity • High programming effort • Trade-off between privacy and efficiency	• Risk of data concentration • Regulatory barriers (e. g., GDPR, antitrust regulation, energy market regulation, contractual agreement requirements, governance, or payment with tokens) • Slow adaptation of current regulations • Low investment security and incomplete, ambiguous legal frameworks • Legally required market roles

The analyzed industry reports and interviews strongly indicate that technical concerns appear to be the easiest to address (Fig. 2). This is in stark contrast to the analyzed literature, where technological challenges are particularly salient but where assessments of blockchain applications remain predominantly theoretical [5,27]. Specifically, challenges resulting from limited performance and high energy-consumption can often be addressed with 'private' designs. Moreover, literature only attaches minor importance to organizational and, in particular, regulatory challenges [6,19]. However, these appear to be important hurdles for many blockchain projects [102]. For certain use cases, such as those focused on *peer-to-peer electricity trading*, addressing the respective challenges would require fundamental changes in the roles and responsibilities of key actors as well as the adjustment of multiple laws. Both industry reports and the interviewed experts deem such changes and adjustments highly unlikely.

4.4. Evaluation of the identified use cases

We evaluated and compared the attributed benefits and challenges for each of the eight use cases using a Likert scale with seven levels (see the Methods section). To depict the evaluation result (Fig. 2), we employed two simple traffic light schemes. For benefits, the color 'green' indicated that literature, industry reports, or experts identified clear benefits of the particular type. We tagged benefits as 'yellow' if their existence was less evident and 'red' if no such benefits were identified for the use case. For challenges, we used a similar scheme to indicate the severity of challenges from manageable ('green') to substantial ('red'). Naturally, these schemes only provided a simplified snapshot of the status quo, but they help to identify quickly if a use case was promising and realizable.

The upper section provides the results from our evaluation of academic literature, whereas the mid-section focuses on industry reports, and the lower on the interviews we conducted. The first column (#) indicates the number of sources that discuss the specific type of benefit or challenge. The second column provides the evaluation of the statements made.

4.4.1. Peer-to-peer electricity trading, decentralized system services and microgrid operation

In terms of benefits, *peer-to-peer electricity trading, decentralized system services,* and *microgrid operation* applications are controversial. While literature, reports, and experts agree that wholesale peer-to-peer markets based on blockchain hardly offer any benefits, they are divided on retail trading, system services, and microgrid operation. This divide is most prominent for retail markets, where experienced experts see few actual benefits of blockchain, studies are ambiguous, and the literature is very positive but hypothetical.

In terms of challenges, there is little controversy. All but a few sources identify considerable challenges from the proposed re-organization of established structures, roles, and processes. For *peer-to-peer electricity trading*, such changes entail substantial challenges of all three types, particularly at the organizational and regulatory levels. The decentralization and disintermediation of trading processes conflict with established roles and regulations, which has slowed the further development of blockchain-based trading platforms. Many of these roles are associated with critical and mediating functions, and their responsibilities are defined by law, which makes them hard to change or replace.

This also applies to *microgrid operation*, where new transaction processes with blockchain would require significant modifications of existing regulations. Even where regulatory frameworks are less restrictive, such as in the US, Thailand, and some African countries, *microgrid operation* is not easy to adopt [5,22,52,103]. Besides, microgrid operators can already process microgrid transactions securely, cheaply, and without regulatory modifications using conventional energy management software [104,105]. Such conventional software solutions also come with predictable management efforts and costs [106]. In contrast, blockchain applications are often more complex and not profitable enough, especially for transactions below a certain value.

From a technological viewpoint, frequent, near-real-time transactions are still difficult to achieve with 'public' blockchains. Thus, decentralized energy markets and microgrid management based on these types of blockchains are also hard to establish technologically. 'Private' blockchains, in contrast, can often provide sufficient transaction speed but typically do not offer the desired level of openness [107].

Consequently, few *peer-to-peer trading* and *microgrid operation* applications have yet taken off. Successful projects exist, however, for *decentralized system services* that cannot be traded effectively on existing markets. One prominent such example is the Equigy platform [108]. The platform allows aggregators to register storage and electric vehicles of their residential customers in a blockchain-based registry. Once registered, these aggregators can use the platform to trade flexibility with transmission and distribution system operators. These transactions are again processed through the blockchain-based registry. The Equigy platform is in productive use since 2021 and has been rolled out in different countries, such as the Netherlands, Germany, and Italy.

4.4.2. E-roaming

E-roaming is an ambiguous use case with unclear efficiency benefits (Fig. 2). Literature, reports, and experts all expect efficiency gains from the automated and standardized transfer of data and the reduction of tedious manual exchanges [41]. Smart contracts and cryptocurrencies may also further automate and unify processes across national borders [109]. These efficiency gains are expected to entail considerable cuts in transaction fees for mobility providers and reduced costs for consumers. Yet, none of the sources provide a precise estimate of these gains.

In contrast, *e-roaming* applications come with various specific regulatory, technological, and organizational challenges. Primarily raised by the interviewed experts, these challenges make the use of blockchain-based charging systems unnecessarily complicated. For instance, cryptocurrency prices can be very volatile and only few users have crypto wallets. Both reasons have brought blockchain based e-roaming platforms to a halt in Germany. Also, governance frameworks need to be established between charging networks and consortia, resulting in costly and time-consuming negotiations. These are, however, necessary as legal uncertainty resulting from unclear governance frameworks and responsibilities may jeopardize customer safety. Another problem is interoperability with existing systems and a lack of standardized and secure interfaces [71,110]. Often, it may be easier to use non-blockchain-based solutions such as conventional platforms that are technologically more mature and easier to implement.

Consequentially, e-roaming applications have so far failed to make it beyond pilot projects. Those applications focusing on transaction processing are weighed down especially by the existence of alternative means of payment, such as credit cards, and those applications focusing on identification and authentication are still stuck at the conceptual level.

4.4.3. Labeling of electricity and certificate trading

Labeling of electricity applications build on expectations of efficiency gains and come with comparatively few challenges (Fig. 2). Blockchain-based labeling systems promise to mitigate concerns regarding the sources of consumed electricity. These systems are expected to reduce the risk of 'greenwashing', accelerate data exchange about fed-in and consumed electricity, and reduce manual processes [73,107]. While these efficiency gains are expected to substantially reduce costs, we were – once again – unable to establish specific estimates.

Specific challenges, in turn, are easier to identify. They include regulatory challenges, for instance, compliance with data privacy regulation, and technological challenges, such as limited usability. Few actors in the energy industry have the technological know-how required to effectively use blockchain technology. Another complex challenge is compliance with data privacy regulations, such as the GDPR. Data privacy regulation requires that data can be erased if it is either directly or indirectly attributable to a natural person, which is difficult to implement with blockchain [111]. As such, labeling systems have to prevent natural persons from being easily identifiable using data stored on the blockchain.

Given these uncertainties, electricity labeling is still at an early stage and most projects remain exploratory. Examples include the InDEED project [112], which explores the use of blockchain to create green and regional labels, and the SMECS project [113], which develops a blockchain-based registry to identify those power generation units from which a customer's electricity was purchased at a particular time.

Certificate trading applications are a new hype that takes the use of blockchain a step further than labeling applications. The idea of most of these applications is to use labeling data as the foundation of certificates of origin or emission for specific generation and storage facilities. Since every certificate is issued uniquely, its secure and redundant storage on the blockchain creates a transparent and unequivocal ownership history. However, quantifying these benefits is difficult. Moreover, the development of an industry-wide or cross-border trading system is highly complex, especially without established technical standards.

Despite these challenges, certain projects have started working on *certificate trading* applications. For instance, the start-up CarbonFuture develops a blockchain-based trading platform for 'carbon removal credits' [114]. Companies can use the platform to fund and trade contributions to carbon removal projects such as biochar sinks that offset their own emissions.

4.4.4. Machine identities

Machine identities are another new hype application; they are expected to generate benefits of all three types. They are argued to increase effectiveness by offering a more flexible, decentralized way of organizing public key infrastructures. Moreover, they are believed to increase the efficiency of processes associated with identifying, (de-) registering, and managing distributed energy resources. In terms of security, these applications could obviate centralized databases for identity information, which would reduce the risk of identity theft and undesirable monitoring by large companies. While these benefits sound promising, they are only hopes at this point and the respective projects have yet to demonstrate that they can be realized and outweigh their costs.

Moreover, *decentralized digital identity* applications are afflicted by many fundamental organizational, technological, and regulatory challenges. These include important governance issues, such as the definition of processes for accrediting issuers of machine identities and the agreement on joint standards for the format of identity credentials. Technological challenges result from limited maturity of technical building blocks as well as limited technological know-how. Regulatory challenges arise, for instance, from privacy requirements as the anchoring of a credential on a blockchain can lead to inadvertent attribution to a natural person.

A prominent example for *machine identity* is the Blockchain Machine Identity Ledger [115] project coordinated by the German Energy Agency (dena). The project investigates the potential of equipping distributed energy resources with machine identities. These identities are expected to enable automated and digital authentication and enable operators to market these resources in a range of electricity markets. Although promising, the Blockchain Machine Identity Ledger is still in the conceptual phase. Another example is a strategic partnership established by the Elia Group and the Energy Web Foundation to explore blockchain-based machine identities for a broad range of use cases in the energy industry [116].

5. Discussion

Blockchain technology has been hyped as a potentially disruptive technology for energy systems. Yet, our analysis of recent academic literature, in addition to practice-informed industry reports and expert interviews, indicates that there is still a long and rocky road ahead for blockchain in Europe. We reveal that expected benefits are often little more than unspecific hopes. Moreover, we find that applications focused on the reorganization of established structures, such as *peer-to-peer electricity trading* or *microgrid operation*, face significant organizational and regulatory barriers, especially in Europe. These barriers make such use cases very hard to realize. Promising projects exist, however, in less regulated areas, such as new markets for *decentralized system services*. These applications address clear and unmet needs in areas that require neither substantial reorganization nor significant regulatory change. Use cases that focus on increasing the efficiency of processes, such as *e-roaming and machine identities*, are feasible yet blockchain may not have enough to offer over alternative technologies. Moreover, such use cases require more than just blockchain technology to succeed. Blockchain may thus best leverage its benefits for energy systems when it takes a backseat.

When we asked the interviewed experts for their opinions on changes required for blockchain to flourish in energy systems, many were outspoken in their criticism of the perceived regulatory uncertainties and barriers. Yet, few could propose specific changes and, even fewer, unbiased recommendations that would not unduly favor blockchain over other technologies. This undifferentiated stance hinders a constructive dialogue with policymakers and regulators, especially when they strongly favor the use of blockchain. Some initiatives have begun to address this divide, particularly for *peer-to-peer electricity trading* applications [22,55]. Other noteworthy developments are the European Union's 'Markets in Crypto-Assets' (MiCA) directive [117], which is expected to reduce regulatory uncertainties for applications that use blockchain for payment purposes, and the revision of the European eIDAS regulation, which will create a European Digital Identity framework [99,118]. Reducing legal uncertainties in highly regulated markets might enable digital innovations to evolve from pilot stages into products that can be safely used by end customers. This, in turn, could increase the number of commercially available products. However, it remains to be seen to what extent such developments will turn the tide.

We thus encourage research and industry to revisit their choice of blockchain applications, especially in Europe, where regulatory challenges are more significant than, for instance, in the US or African countries [5,52,103]. That is, blockchain projects are more likely to succeed when they require few to any regulatory modifications and when they provide competitive solutions for new requirements. Moreover, we encourage a more focused approach that only uses blockchain technology for very specific purposes and combines blockchain with other technologies where these are better suited. Successful applications of blockchain will likely be found in the context of *decentralized system services* but may also become apparent for *certificate trading* or *machine identities* [35,119]. *Microgrid operation* may be useful as well in geographically remote areas that are not connected to a central power grid, such as certain regions in the United States, Australia, or African countries [3,25].

Regarding the technical challenges, we see several promising approaches. Privacy concerns resulting from the replicated processing of transactions on blockchains may be tackled with privacy-enhancing technologies, such as zero-knowledge proofs (ZKPs) [101]. ZKPs allow to verify the validity of a payment or a smart contract call without requiring the distribution of corresponding raw data inputs or outputs to all nodes. Other approaches, such as secure multi-party computation or fully homomorphic encryption, may improve privacy where ZKPs appear infeasible. Yet, these approaches are arguably less mature and would require more research [120].

In addition to privacy issues, the scalability and performance challenges of blockchains may be addressed through incremental improvements or by using 'private' blockchains. Novel concepts such as 'serverless distributed ledgers' may allow for meeting exceptional throughput requirements in private networks [121]. For 'public' blockchains, sharding in combination with scaling solutions like zk-rollups may substantially improve throughput as well [120]. Zk-rollups use ZKPs to compress the computational effort and the storage necessary for the validation of transactions [120]. Such an approach, however, increases system complexity. Moreover, these throughput-enhancing concepts come with a host of other challenges such as tradeoffs between, for instance, throughput and centralization or data availability.

Yet, these technical approaches may also help to address challenges at the regulatory and organizational level. Serverless distributed ledgers, for instance, may provide better cost structures and integration with legacy cloud systems, which often appears to be an acceptable trade-off with increased centralization [121]. Moreover, the use of private blockchains may allow for the retention of traditional market actor roles, which enhances compliance with regulatory frameworks and causes less organizational overhead. Private blockchains are often also better reconcilable with GDPR requirements as they facilitate selective transparency between involved actors [100].

6. Conclusion

Blockchain is no longer just a hype technology, and successful applications exist in various contexts, ranging from food supply chains [1] to public services [28]. However, adoption in energy systems is slow, especially in Europe. In this paper, we investigate the reasons for this slow up-take. Our analysis reveals a stark asymmetry between high hopes and low viability: blockchains expected benefits are often unspecific and hard to quantify, whereas the associated challenges are specific and difficult to resolve. Certain use cases, such as those focusing on peer-to-peer electricity trading, have vague benefits and are difficult to reconcile with regulation, established market structures, and technological requirements. Others, such as e-roaming, entail addressable challenges, yet blockchain fails to offer relevant advantages. Using blockchain to support markets for decentralized system services, certificate trading, or creating machine identities is feasible and promising, but blockchain may only be one part of an effective solution. Blockchain may thus very well have a future in Europe's energy systems – albeit one that is smaller than originally anticipated.

CRediT authorship contribution statement

Tamara Roth: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Visualization. **Manuel Utz:** Conceptualization, Data curation, Formal analysis, Writing – review & editing, Visualization. **Felix Baumgarte:** Conceptualization, Data curation, Formal analysis, Writing – review & editing. **Alexander Rieger:** Conceptualization, Formal analysis, Project administration, Supervision, Writing – review & editing. **Johannes Sedlmeir:** Validation, Writing – review & editing. **Jens Strüker:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Analyzed academic literature

Appendix A1 *List of analyzed academic literature*

Here we list the academic literature that we analyzed to identify benefits and challenges of using blockchain in electric power systems.

Article	Authors	Year	Title	Journal
Ableitner et al. (2020)	Ableitner, L., Tiefenbeck, V., Meeuw, A., Wörner, A., Fleisch, E., & Wortmann, F.	2020	User behavior in a real-world peer-to-peer electricity market.	Applied Energy
Ahl et al. (2019)	Ahl, A., Yarime, M., Tanaka, K., & Sagawa, D.	2019	Review of blockchain-based distributed energy: Implications for institutional development.	Renewable and Sustainable Energy Reviews
Ahl et al. (2020)	Ahl, A., Yarime, M., Goto, M., Chopra, S. S., Kumar, N. M., Tanaka, K., & Sagawa, D.	2020	Exploring blockchain for the energy transition: Opportunities and challenges based on a case study in Japan.	Renewable and Sustainable Energy Reviews
Akter et al. (2020)	Akter, M. N., Mahmud, M. A., Haque, M. E., & Oo, A. M.	2020	An optimal distributed energy management scheme for solving transactive energy sharing problems in residential microgrids.	Applied Energy
Al-Obaidi et al. (2021)	Al-Obaidi, A., Khani, H., Farag, H. E., & Mohamed, M.	2021	Bidirectional smart charging of electric vehicles considering user preferences, peer to peer energy trade, and provision of grid ancillary services.	International Journal of Electrical Power & Energy Systems
AlAshery et al. (2021)	AlAshery, M. K., Yi, Z., Shi, D., Lu, X., Xu, C., Wang, Z., & Qiao, W.	2021	A blockchain-enabled multi-settlement quasi-ideal peer-to-peer trading framework.	IEEE Transactions on Smart Grid
An et al. (2020)	An, J., Lee, M., Yeom, S., & Hong, T.	2020	Determining the Peer-to-Peer electricity trading price and strategy for energy prosumers and consumers within a microgrid.	Applied Energy
Andoni et al. (2019)	Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., … & Peacock, A.	2019	Blockchain technology in the energy sector: A systematic review of challenges and opportunities.	Renewable and Sustainable Energy Reviews
Antal et al. (2021)	Antal, C., Cioara, T., Antal, M., Mihailescu, V., Mitrea, D., Anghel, I., … & Bellesini, F.	2021	Blockchain based decentralized local energy flexibility market.	Energy Reports
Ante et al. (2021)	Ante, L., Steinmetz, F., & Fiedler, I.	2021	Blockchain and energy: A bibliometric analysis and review.	Renewable and Sustainable Energy Reviews
Bandeiras et al. (2020)	Bandeiras, F., Pinheiro, E., Gomes, M., Coelho, P., & Fernandes, J.	2020	Review of the cooperation and operation of microgrid clusters.	Renewable and Sustainable Energy Reviews
Bhushan et al. (2020)	Bhushan, B., Khamparia, A., Sagayam, K. M., Sharma, S. K., Ahad, M. A., & Debnath, N. C.	2020	Blockchain for smart cities: A review of architectures, integration trends and future research directions.	Sustainable Cities and Society
Bian et al. (2022)	Bian, Z., & Zhang, Q.	2022	Combined compromise solution and blockchain-based structure for optimal scheduling of renewable-based microgrids: Stochastic information approach.	Sustainable Cities and Society
Bischi et al. (2021)	Bischi, A., Basile, M., Poli, D., Vallati, C., Miliani, F., Caposciutti, G., … & Desideri, U.	2021	Enabling low-voltage, peer-to-peer, quasi-real-time electricity markets through consortium blockchains.	Applied Energy
Choobineh et al. (2022)	Choobineh, M., Arab, A., Khodaei, A., & Paaso, A.	2022	Energy innovations through blockchain: Challenges, opportunities, and the road ahead.	The Electricity Journal
Christidis et al. (2021)	Christidis, K., Sikeridis, D., Wang, Y., & Devetsikiotis, M.	2021	A framework for designing and evaluating realistic blockchain-based local energy markets.	Applied Energy
Das et al. (2020)	Das, L., Munikoti, S., Natarajan, B., & Srinivasan, B.	2020	Measuring smart grid resilience: Methods, challenges and opportunities.	Renewable and Sustainable Energy Reviews

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Article	Authors	Year	Title	Journal
Di Silvestre et al. (2019)	Di Silvestre, M. L., Gallo, P., Guerrero, J. M., Musca, R., Sanseverino, E. R., Sciumè, G., … & Zizzo, G.	2019	Blockchain for power systems: Current trends and future applications.	Renewable and Sustainable Energy Reviews
Diestelmeier et al. (2019)	Diestelmeier, L.	2019	Changing power: Shifting the role of electricity consumers with blockchain technology–Policy implications for EU electricity law.	Energy Policy
Doan et al. (2021)	Doan, H. T., Cho, J., & Kim, D.	2021	Peer-to-peer energy trading in smart grid through blockchain: A double auction-based game theoretic approach.	IEEE Access
Dong et al. (2018)	Dong, Z., Luo, F., & Liang, G.	2018	Blockchain: a secure, decentralized, trusted cyber infrastructure solution for future energy systems.	Journal of Modern Power Systems and Clean Energy
Esfahani (2022)	Esfahani, M. M.	2022	A hierarchical blockchain-based electricity market framework for energy transactions in a security-constrained cluster of microgrids.	International Journal of Electrical Power & Energy Systems
Esmat et al. (2021)	Esmat, A., de Vos, M., Ghiassi-Farrokhfal, Y., Palensky, P., & Epema, D.	2021	A novel decentralized platform for peer-to-peer energy trading market with blockchain technology.	Applied Energy
Foti & Vavalis (2019)	Foti, M., & Vavalis, M.	2019	Blockchain based uniform price double auctions for energy markets.	Applied Energy
Fu et al. (2020)	Fu, Z., Dong, P., & Ju, Y.	2020	An intelligent electric vehicle charging system for new energy companies based on consortium blockchain.	Journal of Cleaner Production
Guerrero et al. (2020)	Guerrero, J., Gebbran, D., Mhanna, S., Chapman, A. C., & Verbič, G.	2020	Towards a transactive energy system for integration of distributed energy resources: Home energy management, distributed optimal power flow, and peer-to-peer energy trading.	Renewable and Sustainable Energy Reviews
Guerrero et al. (2021)	Guerrero, J., Sok, B., Chapman, A. C., & Verbič, G.	2021	Electrical-distance driven peer-to-peer energy trading in a low-voltage network.	Applied Energy
Hahnel et al. (2019)	Hahnel, U. J., Herberz, M., Pena-Bello, A., Parra, D., & Brosch, T.	2019	Becoming prosumer: Revealing trading preferences and decision-making strategies in peer-to-peer energy communities.	Energy Policy
Han et al. (2020)	Han, D., Zhang, C., Ping, J., & Yan, Z.	2020	Smart contract architecture for decentralized energy trading and management based on blockchains.	Energy
Hasankhani et al. (2021)	Hasankhani, A., Hakimi, S. M., Bisheh-Niasar, M., Shafie-khah, M., & Asadolahi, H.	2021	Blockchain technology in the future smart grids: A comprehensive review and frameworks.	International Journal of Electrical Power & Energy Systems
Hayes et al. (2020)	Hayes, B. P., Thakur, S., & Breslin, J. G.	2020	Co-simulation of electricity distribution networks and peer to peer energy trading platforms.	International Journal of Electrical Power & Energy Systems
Hirsch et al. (2018)	Hirsch, A., Parag, Y., & Guerrero, J.	2018	Microgrids: A review of technologies, key drivers, and outstanding issues.	Renewable and Sustainable Energy Reviews
Howson (2019)	Howson, P.	2019	Tackling climate change with blockchain.	Nature Climate Change
Hua et al. (2020)	Hua, W., Jiang, J., Sun, H., & Wu, J.	2020	A blockchain based peer-to-peer trading framework integrating energy and carbon markets.	Applied Energy
Jiang et al. (2020)	Jiang, Y., Zhou, K., Lu, X., & Yang, S.	2020	Electricity trading pricing among prosumers with game theory-based model in energy blockchain environment.	Applied Energy
Johnson & Mayfield (2020)	Johnson, R. C., & Mayfield, M.	2020	The economic and environmental implications of post feed-in tariff PV on constrained low voltage networks.	Applied Energy
Kanakadhurga et al. (2022)	Kanakadhurga, D., & Prabaharan, N.	2022	Demand side management in microgrid: A critical review of key issues and recent trends.	Renewable and Sustainable Energy Reviews
Khan et al. (2019)	Khan, F. A., Asif, M., Ahmad, A., Alharbi, M., & Aljuaid, H.	2019	Blockchain technology, improvement suggestions, security challenges on smart grid and its application in healthcare for sustainable development.	Sustainable Cities and Society
Khorasany et al. (2021)	Khorasany, M., Dorri, A., Razzaghi, R., & Jurdak, R.	2021	Lightweight blockchain framework for location-aware peer-to-peer energy trading.	International Journal of Electrical Power & Energy Systems
Kobashi et al. (2020)	Kobashi, T., Yoshida, T., Yamagata, Y., Naito, K., Pfenninger, S., Say, K., … & Hara, K.	2020	On the potential of “Photovoltaics + Electric vehicles” for deep decarbonization of Kyoto’s power systems: Techno-economic-social considerations.	Applied Energy
Lei et al. (2021)	Lei, N., Masanet, E., & Koomey, J.	2021	Best practices for analyzing the direct energy use of blockchain technology systems: Review and policy recommendations.	Energy Policy
Li et al. (2018)	Li, Z., Shahidehpour, M., & Liu, X.	2018	Cyber-secure decentralized energy management for IoT-enabled active distribution networks.	Journal of Modern Power Systems and Clean Energy
Li et al. (2019)	Li, Y., Yang, W., He, P., Chen, C., & Wang, X.	2019	Design and management of a distributed hybrid energy system through smart contract and blockchain.	Applied Energy
Li et al. (2021)	Li, S., Pan, Y., Xu, P., & Zhang, N.	2021	A decentralized peer-to-peer control scheme for heating and cooling trading in distributed energy systems.	Journal of Cleaner Production
Lin et al. (2019)	Lin, J., Pipattanasomporn, M., & Rahman, S.	2019	Comparative analysis of auction mechanisms and bidding strategies for P2P solar transactive energy markets.	Applied Energy
Long et al. (2018)	Long, C., Wu, J., Zhou, Y., & Jenkins, N.	2018	Peer-to-peer energy sharing through a two-stage aggregated battery control in a community Microgrid.	Applied Energy
Lowitzsch et al. (2020)	Lowitzsch, J., Hoicka, C. E., & van Tulder, F. J.	2020	Renewable energy communities under the 2019 European Clean Energy Package–Governance model for the energy clusters of the future?.	Renewable and Sustainable Energy Reviews
Luo et al. (2018)	Luo, F., Dong, Z. Y., Liang, G., Murata, J., & Xu, Z.	2018	A distributed electricity trading system in active distribution networks based on multi-agent coalition and blockchain.	IEEE Transactions on Power Systems
Lüth et al. (2018)	Lüth, A., Zepter, J. M., del Granado, P. C., & Egging, R.	2018	Local electricity market designs for peer-to-peer trading: The role of battery flexibility.	Applied Energy
Maneesha & Swarup (2021)	Maneesha, A., & Swarup, K. S.	2021	A survey on applications of Alternating Direction Method of Multipliers in smart power grids.	Renewable and Sustainable Energy Reviews
Mehdinejad et al. (2022)	Mehdinejad, M., Shayanfar, H. A., Mohammadi-Ivatloo, B., … & Nafisi, H.	2022	Designing a Robust Decentralized Energy Transactions Framework for Active Prosumers in Peer-to-Peer Local Electricity Markets.	IEEE Access

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Article	Authors	Year	Title	Journal
Mengelkamp et al. (2018)	Mengelkamp, E., Gärttner, J., Rock, K., Kessler, S., Orsini, L., & Weinhardt, C.	2018	Designing microgrid energy markets: A case study: The Brooklyn Microgrid.	Applied Energy
Mengelkamp et al. (2019)	Mengelkamp, E., Schlund, D., & Weinhardt, C.	2019	Development and real-world application of a taxonomy for business models in local energy markets.	Applied Energy
Mika et al. (2021)	Mika, B., & Goudz, A.	2021	Blockchain-technology in the energy industry: Blockchain as a driver of the energy revolution? With focus on the situation in Germany.	Energy Systems
Milchram et al. (2020)	Milchram, C., Künneke, R., Doorn, N., van de Kaa, G., & Hillerbrand, R.	2020	Designing for justice in electricity systems: A comparison of smart grid experiments in the Netherlands.	Energy Policy
Neves et al. (2020)	Neves, D., Scott, I., & Silva, C. A.	2020	Peer-to-peer energy trading potential: An assessment for the residential sector under different technology and tariff availabilities.	Energy
Noor et al. (2018)	Noor, S., Yang, W., Guo, M., van Dam, K. H., & Wang, X.	2018	Energy demand side management within micro-grid networks enhanced by blockchain.	Applied Energy
Nour et al. (2022)	Nour, M., Chaves-Ávila, J. P., & Sánchez-Miralles, Á.	2022	Review of Blockchain Potential Applications in the Electricity Sector and Challenges for Large Scale Adoption.	IEEE Access
Paiho et al. (2021)	Paiho, S., Kiljander, J., Sarala, R., Siikavirta, H., Kilkki, O., Bajpai, A., … & Weisshaupt, T.	2021	Towards cross-commodity energy-sharing communities–A review of the market, regulatory, and technical situation.	Renewable and Sustainable Energy Reviews
Perrons et al. (2020)	Perrons, R. K., & Cosby, T.	2020	Applying blockchain in the geoenergy domain: The road to interoperability and standards.	Applied Energy
Prinsloo et al. (2018)	Prinsloo, G., Dobson, R., & Mammoli, A.	2018	Synthesis of an intelligent rural village microgrid control strategy based on smartgrid multi-agent modelling and transactive energy management principles.	Energy
Roberts et al. (2019)	Roberts, M. B., Bruce, A., & MacGill, I.	2019	Opportunities and barriers for photovoltaics on multi-unit residential buildings: Reviewing the Australian experience.	Renewable and Sustainable Energy Reviews
Saha et al. (2021)	Saha, S., Ravi, N., Hreinsson, K., Baek, J., Scaglione, A., & Johnson, N. G.	2021	A secure distributed ledger for transactive energy: The Electron Volt Exchange (EVE) blockchain.	Applied Energy
Soto et al. (2021)	Soto, E. A., Bosman, L. B., Wollega, E., & Leon-Salas, W. D.	2021	Peer-to-peer energy trading: A review of the literature.	Applied Energy
Sousa et al. (2019)	Sousa, T., Soares, T., Pinson, P., Moret, F., Baroche, T., & Sorin, E.	2019	Peer-to-peer and community-based markets: A comprehensive review.	Renewable and Sustainable Energy Reviews
Thomas et al. (2019)	Thomas, L., Zhou, Y., Long, C., Wu, J., & Jenkins, N.	2019	A general form of smart contract for decentralized energy systems management.	Nature Energy
Thukral (2021)	Thukral, M. K.	2021	Emergence of blockchain-technology application in peer-to-peer electrical-energy trading: a review.	Clean Energy
Tsao & Thanh (2021)	Tsao, Y. C., & Thanh, V. V.	2021	Toward blockchain-based renewable energy microgrid design considering default risk and demand uncertainty.	Renewable Energy
Tsao et al. (2021)	Tsao, Y. C., & Thanh, V. V.	2021	Toward sustainable microgrids with blockchain technology-based peer-to-peer energy trading mechanism: A fuzzy *meta*-heuristic approach.	Renewable and Sustainable Energy Reviews
Tsao, Thanh & Wu (2021)	Tsao, Y. C., Thanh, V. V., & Wu, Q.	2021	Sustainable microgrid design considering blockchain technology for real-time price-based demand response programs.	International Journal of Electrical Power & Energy Systems
Tushar et al. (2021)	Tushar, W., Yuen, C., Saha, T. K., Morstyn, T., Chapman, A. C., Alam, M. J. E., … & Poor, H. V.	2021	Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges.	Applied Energy
van Cutsem et al. (2020)	Van Cutsem, O., Dac, D. H., Boudou, P., & Kayal, M.	2020	Cooperative energy management of a community of smart-buildings: A Blockchain approach.	International Journal of Electrical Power & Energy Systems
van Leeuwen et al. (2020)	van Leeuwen, G., AlSkaif, T., Gibescu, M., & van Sark, W.	2020	An integrated blockchain-based energy management platform with bilateral trading for microgrid communities.	Applied Energy
Vieira & Zhang (2021)	Vieira, G., & Zhang, J.	2021	Peer-to-peer energy trading in a microgrid leveraged by smart contracts.	Renewable and Sustainable Energy Reviews
Wang et al. (2019)	Wang, C. S., Yan, J. Y., Jia, H. J., Wu, J. Z., Yu, J. C., Xu, T., & Zhang, Y.	2019	Renewable and distributed energy integration with mini/microgrids.	Applied Energy
Wang et al. (2020)	Wang, L., Liu, J., Yuan, R., Wu, J., Zhang, D., Zhang, Y., & Li, M.	2020	Adaptive bidding strategy for real-time energy management in multi-energy market enhanced by blockchain.	Applied Energy
Wang et al. (2021)	Wang, B., Zhao, S., Li, Y., Wu, C., Tan, J., Li, H., & Yukita, K.	2021	Design of a privacy-preserving decentralized energy trading scheme in blockchain network environment.	International Journal of Electrical Power & Energy Systems
Warneryd et al. (2020)	Warneryd, M., Håkansson, M., & Karltorp, K.	2020	Unpacking the complexity of community microgrids: A review of institutions' roles for development of microgrids.	Renewable and Sustainable Energy Reviews
Wu & Zhang (2021)	Wu, Y., Zhang, X., & Sun, H.	2021	A multi-time-scale autonomous energy trading framework within distribution networks based on blockchain.	Applied Energy
Wu et al. (2019)	Wu, J., Hu, J., Ai, X., Zhang, Z., & Hu, H.	2019	Multi-time scale energy management of electric vehicle model-based prosumers by using virtual battery model.	Applied Energy
Wu et al. (2021)	Wu, Y., Wu, Y., Guerrero, J. M., & Vasquez, J. C.	2021	Digitalization and decentralization driving transactive energy Internet: Key technologies and infrastructures.	International Journal of Electrical Power & Energy Systems
Yan et al. (2022)	Yan, M., Gan, W., Zhou, Y., Wen, J., & Yao, W.	2022	Projection method for blockchain-enabled non-iterative decentralized management in integrated natural gas-electric systems and its application in digital twin modelling.	Applied Energy
Yazdanie et al. (2021)	Yazdanie, M., & Orehounig, K.	2021	Advancing urban energy system planning and modeling approaches: Gaps and solutions in perspective.	Renewable and Sustainable Energy Reviews
Yun et al. (2021)	Yun, G., Zhygulin, V., & Zheng, Q. P.	2021	Residential energy trading with blockchain technology.	Energy Systems
Zhang et al. (2018)	Zhang, T., Pota, H., Chu, C. C., & Gadh, R.	2018	Real-time renewable energy incentive system for electric vehicles using prioritization and cryptocurrency.	Applied Energy

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Article	Authors	Year	Title	Journal
Zhang et al. (2019)	Zhang, H., Wang, J., & Ding, Y.	2019	Blockchain-based decentralized and secure keyless signature scheme for smart grid.	Energy
Zhang et al. (2020)	Zhang, S., Rong, J., & Wang, B.	2020	A privacy protection scheme of smart meter for decentralized smart home environment based on consortium blockchain.	Journal of Electrical Power & Energy Systems
Zhang et al. (2022)	Zhang, Q., Su, Y., Wu, X., Zhu, Y., & Hu, Y.	2022	Electricity trade strategy of regional electric vehicle coalitions based on blockchain.	Electric Power Systems Research
Zhao et al. (2022)	Zhao, S., Zhu, S., Wu, Z., & Jaing, B.	2022	Cooperative energy dispatch of smart building cluster based on smart contracts.	International Journal of Electrical Power & Energy Systems

Analyzed industry reports

Appendix A2 *List of analyzed industry reports*

Here we list the industry reports that we analyzed to identify benefits and challenges of using blockchain in electric power systems.

Report	Organization	Year	Title
Accenture (2018)	Accenture	2018	Blockchain for Utilities: Beyond the Buzz
Adelphi (2019)	Adelphi Consult and Wuppertal Institute	2019	Smart power grids and integration of renewables in Japan. Current activities concerning smart grids implementation, energy system digitization and integration of renewables
Atlantic Council (2019)	Atlantic Council Global Energy Center	2019	Assessing Blockchain's Future in Transactive Energy
Bitkom (2020)	Bitkom e. V. Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e. V.	2020	Self Sovereign Identity Use Cases – von der Vision in die Praxis
EU Blockchain Observatory and Forum (2019)	European Union Blockchain Observatory and Forum	2019	Blockchain and Digital Identity
BNetzA (2019)	German Federal Network Agency (Bundesnetzagentur)	2020	Die Blockchain-Technologie - Potenziale und Herausforderungen in den Netzsektoren Energie und Telekommunikation
Bundesblock (2019)	Blockchain Bundesverband	2019	Aktionspapier des Blockchain Bundesverband e.V. zur Blockchain-Strategie der Bundesregierung
Capgemini (2019)	Capgemini	2019	World Energy Markets Observatory 2019
CDC Canada (2019)	Chamber of Digital Commerce Canada	2019	Canadian Blockchain Census 2019. Part I: Measuring Canada's Blockchain Ecosystem
CLI (2019)	Climate Ledger Initiative	2019	Navigating Blockchain and Climate Action
Cognizant (2018)	Cognizant	2018	Blockchain for Power Utilities: A View on Capabilities and Adoption
Congressional Research Service (2019)	Congressional Research Service (USA)	2019	Bitcoin, Blockchain, and the Energy Sector
Council on Foreign Relations (2018)	Council on Foreign Relations (USA)	2018	Applying Blockchain Technology to Electric Power Systems
CSIS (2019)	Center for Strategic and International Studies	2019	Blockchain and Aggregating Microgrid Projects in Developing Nations in: New Perspectives in Foreign Policy
Deloitte (2019)	Deloitte	2019	Blockchain: A true disruptor for the energy industry. Use cases and strategic questions
DENA (2019)	German Energy Agency (DENA)	2019	Blockchain in the integrated energy transition
Detecon (2018)	Detecon	2018	Blockchain Disruptively Changing the Energy Industry
Energy Futures Initiative (2018)	Energy Futures Initiative	2018	Promising Blockchain Applications for Energy: Separating the Signal from the Noise
EnergyWeb (2019)	Energy Web Foundation	2019	The Energy Web Chain - Accelerating the Energy Transition with an Open-Source, Decentralized Blockchain Platform
Enisa (2022)	European Union Agency for Cybersecurity (ENISA)	2022	Digital Identity - Leveraging the Self-Sovereign Identity (SSI)Concept to Build Trust
EU Blockchain Observatory and Forum (2019)	European Union Blockchain Observatory and Forum	2019	EU Blockchain Observatory & Forum - Energy and Sustainability
European Commission (2019)	European Commission	2019	Blockchain Now and Tomorrow: Assessing Multidimensional Impacts of Distributed Ledger Technologies
EY (2019)	Ernst & Young	2019	Blockchain-basierte Erfassung und Steuerung von Energieanlagen mithilfe des Smart-Meter-Gateways: Machbarkeitsstudie und Pilotkonzept
FFE (2018)	Forschungsstelle für Energiewirtschaft	2018	Die Blockchain-Technologie - Chance zur Transformation der Energiewirtschaft? Berichtsteil: Anwendungsfälle
Fraunhofer FIT (2021)	Project Group Business & Information Systems Engineering of the Fraunhofer Institute for Applied Information Technology FIT, Bayreuth.	2021	Self-Sovereign Identity Foundations, Applications, and Potentials of Portable Digital Identities
FSR (2019)	German-Mexican Energy Partnership (EP) and Florence School of Regulation (FSR)	2019	Blockchain meets Energy - Digital Solutions for a Decentralized and Decarbonized Sector
Germanwatch (2018)	Germanwatch	2018	Blockchain – Opportunities and threats for the energy transition
GIZ Mexico (2019)	German Corporation for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit - GIZ)	2019	Blockchain in the Mexican Energy Sector - Fostering digital transformation

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Report	Organization	Year	Title
IFC (2018)	International Finance Corporation	2018	Using Blockchain to Enable Cleaner, Modern Energy Systems in Emerging Markets
IRENA (2019)	International Renewable Energy Agency	2019	Innovation landscape brief: Blockchain
NERA (2019)	NERA Economic Consulting	2019	Blockchain in Electricity: a Critical Review of Progress to Date
Netherlands Innovation Network (2019)	Netherlands Enterprise Agency	2019	Blockchain - Netherlands Innovation Network
NITI Aayog (2019)	NITI Aayog	2019	Blockchain: The India Strategy
NREL (2020)	National Renewable Energy Laboratory	2020	The Evolving U.S. Distribution System: Technologies, Architectures, and Regulations for Realizing a Transactive Energy Marketplace
Renew Nexus (2019)	RENeW Nexus	2019	Enabling resilient, low cost & localized electricity markets through blockchain P2P & VPP trading
SAP (2018)	SAP	2018	Blockchain in the Energy Sector - The Potential for Energy Providers
Smart Service Welt (2020)	Smart Service Welt	2020	Energierevolution getrieben durch Blockchain
Solarplaza (2019)	Solarplaza	2019	Comprehensive Guide to Companies involved in Blockchain & Energy
Stanford (2019)	Stanford Graduate School of Business	2019	Blockchain for Social Impact - Moving Beyond the Hype
UTCID Report (2021)	The University of Texas at Austin Center for Identity	2021	Blockchain-Based Self-Sovereign Identity: Survey, Requirements, Use-Cases, and Comparative Study
Vise (2019)	Virtual Institut Smart Energy (VISE)	2019	Blockchain in der Energiewirtschaft
World Energy Council (2019)	World Energy Council	2019	The Developing Role of Blockchain

Interview guide

Appendix A3 *Interview guide*

1. **Presentation of the research project's objectives (5 min)**
   a. **General information**
   o Explain the purpose and details of the interview and data processing
   o Request permission to record the interview
   o Restatement of the purpose of the agreement and acknowledgement of the interviewee.
   b. **Presentation of the research project**
   o We investigate promising blockchain use cases in the energy industry
   o We examine both benefits and challenges associated with blockchain applications
   o We want to identify where the use of blockchain technology makes sense
2. **Introduction of the interviewee (5 min)**
   o Ask the interviewee to briefly introduce their organization
   o Ask the interviewee to briefly their role in the organization and the length of their affiliation
   o Ask the interviewee to state how long they have been in their current role or field
   o Ask the interviewee to present their professional background
3. **Discussion of the use case or pilot project in which the interviewee was/is involved (35 min)**
   a. **General**
   o What is the use case or project scope?
   - What was done?
   - Which partners were involved?
   - How long did the project last?
   - What were the cost of the project?

   b. **Role of blockchain**
   o Why was blockchain used in the project / which added value did it bring to the table?
   o Which blockchain framework (Ethereum, Hyperledger, etc.) was used and why?
   o Which Blockchain components were adapted and which were used "out of the box"?
   o How were the blockchain components integrated into existing systems? (e.g., data transfer from existing systems, etc.).
   o What does an exemplary process of data processing, storage, and transfer look like for the use case / the pilot project?
   o Where did blockchain-specific challenges arise over the course of the project and how did you solve them?
   c. **Recommendations for action**
   o Based on the challenges identified, what do you expect from:
   - **political decision-makers?** (Adopt legislation to facilitate implementation? Create a new policy framework? What should this framework look like?)
   - the **scientific community?** (In which area would research need to be intensified? Are "sandboxes" useful? In which area would collaboration between research and industry need to be improved?)
   - other **companies/ the market?** (Is the competition too strong / too weak? Should there be more collaboration between start-ups and established companies)?

Interviewed experts

Appendix A4 *List of interviewed experts*

Here we list the interviews that we conducted to identify benefits and challenges of using blockchain in electric power systems. For privacy reasons, we do not list the names of the interviewed experts and their organizations.

Interview No.	Job Title	Organization Type	Organization No.	Discussed Use Cases
1	Product and Partner Manager	Non Profit Organization	1	Peer-to-peer electricity trading - retail, E-roaming, Certificate trading
2	CEO	IT Service Provider	2	Peer-to-peer electricity trading - retail, Peer-to-peer electricity trading - wholesale
3	Blockchain Engineer	Non Profit Organization	3	Decentralized system services, Labeling of electricity, Certificate trading
4	Lead Blockchain and Distributed Ledger Technologies	Energy Utility	3	Peer-to-peer electricity trading - retail, Labeling of electricity
5	Director Operations	IT Service Provider	4	Certificate trading
6	Chief Security Officer	IT Service Provider	5	Peer-to-peer electricity trading - retail
7	Product and Innovation Manager	IT Service Provider	6	Labeling of electricity, Certificate trading
8	Product Manager	IT Service Provider	5	Peer-to-peer electricity trading - retail
9	Head of Distributed Ledger Technologies	IT Service Provider	7	Peer-to-peer electricity trading - retail, Decentralized system services, E-roaming
10	Head of Business Relationship Management	Energy Utility	8	Peer-to-peer electricity trading - retail, Decentralized system services, Certificate trading
11	IT Project Manager	Distribution System Operator	9	Peer-to-peer electricity trading - retail, Decentralized system services
12	Head of Energy Data Lab	Energy Utility	10	Peer-to-peer electricity trading - retail, E-roaming
13	Distributed Ledger Software Engineer	Energy Utility	10	E-roaming
14	Team Leader Local Energy Platforms	Research Institute	11	Peer-to-peer electricity trading - retail
15	Researcher	Research Institute	12	Peer-to-peer electricity trading - retail, Certificate trading
16	Lawyer and Partner	Law Firm	13	Microgrid operation
17	Researcher	Research Institute	14	Peer-to-peer electricity trading - retail
18	Project Manager	Energy Think Tank	15	Peer-to-peer electricity trading - retail
19	Senior Technical Manager	IT Service Provider	16	Peer-to-peer electricity trading - retail
20	CEO and Founder	IT Management Consultancy	17	Peer-to-peer electricity trading - retail
21	Head of Technology Lab	Energy Service Provider	18	Peer-to-peer electricity trading - retail
22	Software Developer	Research Institute	19	Peer-to-peer electricity trading - wholesale, Microgrid operation
23	Embedded Systems Developer	IT Service Provider	20	Peer-to-peer electricity trading - retail
24	Electrical Engineer	Research Institute	19	Microgrid operation
25	CTO	Non Profit Organization	1	E-roaming
26	Lead Technical Solutions and Product Quality	IT Service Provider	21	Labeling of electricity
27	Attorney-at-law	Consumer Protection Association	22	Peer-to-peer electricity trading - retail
28	Head of Communication and Energy Policy	Energy utility	23	Peer-to-peer electricity trading - wholesale, labeling of electricity
29	Energy Expert	Energy Trading House	24	Peer-to-peer electricity trading - wholesale, Decentralized system services, labeling of electricity
30	Head of Market Management Department	Distribution System Operator	25	Decentralized system services
31	Researcher	Research Institute	26	Peer-to-peer electricity trading - wholesale, Decentralized system services, Microgrid operation, Labeling of electricity, Certificate trading
32	Researcher	Research Institute	27	Peer-to-peer electricity trading - retail, Peer-to-peer electricity trading - wholesale, Microgrid operation, E-roaming
33	Researcher	Research Institute	27	Peer-to-peer electricity trading - wholesale, Microgrid operation, E-roaming
34	Head of Venture Creation	IT Service Provider	28	Peer-to-peer electricity trading - retail, Microgrid operation, E-roaming
35	Head of Sales and Business Area Development	Start-Up	29	Peer-to-peer electricity trading - retail, Labeling of electricity, Certificate trading
36	Researcher	Research Institute	30	Labeling of electricity, Certificate trading
37	Researcher	Research Institute	30	Peer-to-peer electricity trading - wholesale, Decentralized system services, Microgrid operation, Labeling of electricity, Certificate trading
38	Partnership Development and Regulatory Affairs	Non Profit Organization	31	Peer-to-peer electricity trading - wholesale, Decentralized system services, Microgrid operation
39	Lead IoT Architect and Software Developer	Energy Utility	32	Peer-to-peer electricity trading - retail, Decentralized system services, Microgrid operation, Labeling of electricity, Certificate trading
40	Blockchain Product Owner	Energy Utility	32	Peer-to-peer electricity trading - wholesale, Microgrid operation, Labeling of electricity
41	Founder and CEO	Start-Up	33	Machine identities, Labeling of electricity; Peer-to-peer electricity trading - retail

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Interview No.	Job Title	Organization Type	Organization No.	Discussed Use Cases
42	Founder and CEO	Start-Up	34	Machine identities
43	Researcher	Research Institute	35	Machine identities, Peer-to-peer electricity trading - retail, E-roaming
44	Blockchain Architect and Head of SSI	Start-Up	36	Machine identities
45	Co-Founder and CEO	Start-Up	37	Machine identities, Labeling of electricity, Certificate trading, Peer-to-peer electricity trading - retail, Decentralized system services, Microgrid operation

Use case analysis

Appendix A5 *Analyzed sources per use case*

Here we list the sources on which we based our analysis of the identified use cases.

Use Case	Sources
Peer-to-peer electricity trading – retail	**Literature** Ableitner et al. (2020), Ahl et al. (2019), Ahl et al. (2020), Akter et al. (2020), Al-Obaidi et al. (2021), AlAshery et al. (2021), An et al. (2020), Andoni et al. (2019), Antal et al. (2021), Ante et al. (2021), Bischi et al. (2021), Choobineh et al. (2022), Christidis et al. (2021), Di Silvestre et al. (2019), Diestelmeier et a. (2019), Doan et al. (2021), Dong et al. (2018), Esfahani (2022), Esmat et al. (2021), Foti & Vavalis (2019), Guerrero et al. (2020), Guerrero et al. (2021), Hahnel et al. (2019), Han et al. (2020), Hasankhani et al. (2021), Hayes et al. (2020), Hirsch et al. (2018), Hua et al. (2020), Jiang et al. (2020), Johnson & Mayfield (2020), Kanakadhurga et al. (2022), Khorasany et al. (2021), Kobashi et al. (2020), Lei et al. (2021), Li et al. (2018), Li et al. (2019), Lin et al. (2019), Long et al. (2018), Lowitzsch et al. (2020), Luo et al. (2018), Lüth et al. (2018), Maneesha & Swarup (2021), Mehdinejad et al. (2022), Mengelkamp et al. (2018), Mengelkamp et al. (2019), Mika et al. (2021), Milchram et al. (2020), Neves et al. (2020), Noor et al. (2018), Nour et al. (2022), Paiho et al. (2021), Perrons et al. (2020), Prinsloo et al. (2018), Roberts et al. (2019), Saha et al. (2021), Soto et al. (2021), Sousa et al. (2019), Thukral (2021), Tsao & Thanh (2021), Tushar et al. (2021), van Cutsem et al. (2020), van Leeuwen et al. (2020), Vieira & Zhang (2021), Wang et al. (2020), Wang et al. (2021), Warneryd et al. (2020), Wu &, Zhang (2021), Wu et al. (2019), Wu et al. (2021), Yun et al. (2021), Zhao et al. (2022) **Reports** Accenture (2018), Atlantic Council (2019), BNetzA (2019), Bundesblock (2019), Capgemini (2019), CDC Canada (2019), CLI (2019), Congressional Research Service (2019), Council on Foreign Relations (2018), Deloitte (2019), Detecon (2018), Energy Futures Initiative (2018), EU Blockchain Observatory and Forum (2019), FFE (2018), FSR (2019), Germanwatch (2018), IFC (2018), IRENA (2019), NERA (2019), NREL (2020), Renew Nexus (2019), SAP (2018), Smart Service Welt (2020), Solarplaza (2019), Stanford (2019), Vise (2019), World Energy Council (2019) **Interviews** 1, 2, 4, 6, 8, 9, 10, 11, 12, 14, 15, 17, 18, 19, 20, 21, 23, 27, 32, 34, 35, 39, 40, 41, 43, 45
Peer-to-peer electricity trading - wholesale	**Literature** Ableitner et al. (2020), Ahl et al. (2019), Ahl et al. (2020), An et al. (2020), Andoni et al. (2019), Antal et al. (2021), Ante et al. (2021), Bhushan et al. (2020), Choobineh et al. (2022), Choobineh et al. (2022), Di Silvestre et al. (2019), Diestelmeier et al. (2019), Dong et al. (2018), Esmat et al. (2021), Foti & Vavalis (2019), Han et al. (2020), Han et al. (2020), Hasankhani et al. (2021), Hayes et al. (2020), Johnson & Mayfield (2020), Li et al. (2018), Li et al. (2021), Lin et al. (2019), Maneesha & Swarup (2021), Maneesha et al. (2021), Mengelkamp et al. (2019), Mika et al. (2021), Noor et al. (2018), Nour et al. (2022), Paiho et al. (2021), Perrons et al. (2020), Soto et al. (2021), Sousa et al. (2019), Thukral (2021), Tushar et al. (2021), Wang et al. (2020), Wang et al. (2021), Wu et al. (2019), Wu et al. (2021), Yan et al. (2022) **Reports** Accenture (2018), Council on Foreign Relations (2018), DENA (2019), Detecon (2018), Energy Futures Initiative (2018), EY (2019), FFE (2018), FSR (2019), Germanwatch (2018), GIZ Mexico (2019), NERA (2019), Renew Nexus (2019), Solarplaza (2019) **Interviews** 2, 22, 28, 29, 31, 32, 33, 37, 38, 40
Decentralized system services	**Literature** Ahl et al. (2019), Christidis et al. (2021), Lin et al. (2019), Ableitner et al. (2020), Ahl et al. (2020), Al-Obaidi et al. (2021), An et al. (2020), Andoni et al. (2019), Ante et al. (2021), Choobineh et al. (2022), Di Silvestre et al. (2019), Diestelmeier et a. (2019), Dong et al. (2018), Esmat et al. (2021), Foti & Vavalis (2019), Guerrero et al. (2020), Han et al. (2020), Hasankhani et al. (2021), Hayes et al. (2020), Kanakadhurga et al. (2022), Lei et al. (2021), Li et al. (2018), Li et al. (2021), Mengelkamp et al. (2019), Mika et al. (2021), Noor et al. (2018), Paiho et al. (2021), Roberts et al. (2019), Soto et al. (2021), Sousa et al. (2019), Thukral (2021), Tsao et al. (2021), Tushar et al. (2021), Wang et al. (2020), Wang et al. (2021), Yan et al. (2022) **Reports** BNetzA (2019), DENA (2019), EnergyWeb (2019), FFE (2018), FSR (2019), Germanwatch (2018), IRENA (2019), NERA (2019), NREL (2020), Renew Nexus (2019), SAP (2018), Smart Service Welt (2020) **Interviews** 3, 9, 10, 11, 29, 30, 31, 37, 38, 39, 45
Microgrid operation	**Literature** Ahl et al. (2019), Ahl et al. (2020), Andoni et al. (2019), Antal et al. (2021), Ante et al. (2021), Bandeiras et al. (2020), Bhushan et al. (2020), Bian et al. (2022), Choobineh et al. (2022), Christidis et al. (2021), Das et al. (2020), Di Silvestre et al. (2019), Diestelmeier et a. (2019), Dong et al. (2018), Esfahani (2022), Esmat et al. (2021), Hasankhani et al. (2021), Hayes et al. (2020), Kanakadhurga et al. (2022), Khan et al. (2019), Khorasany et al. (2021), Kobashi et al. (2020), Li et al. (2018), Li et al. (2019), Long et al. (2018), Luo et al. (2018), Maneesha & Swarup (2021), Mengelkamp et al. (2018), Mengelkamp et al. (2019), Noor et al. (2018), Nour et al. (2022), Paiho et al. (2021), Perrons et al. (2020), Prinsloo et al. (2018), Roberts et al. (2019), Soto et al. (2021), Tsao & Thanh (2021), Tsao et al. (2021), Tsao, Thanh & Wu (2021), Tushar et al. (2021), van Cutsem et al. (2020), van Leeuwen et al. (2020), Vieira & Zhang (2021), Wang et al. (2019), Wang et al. (2020), Wu et al. (2021), Zhang et al. (2018), Zhang et al. (2020), Zhao et al. (2022) **Reports** Atlantic Council (2019), Capgemini (2019), CLI (2019), Council on Foreign Relations (2018), CSIS (2019), Deloitte (2019), Energy Futures

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Use Case	Sources
	Initiative (2018), EnergyWeb (2019), FFE (2018), FSR (2019), IFC (2018), IRENA (2019), NERA (2019), Netherlands Innovation Network (2019), NITI Aayog (2019), Renew Nexus (2019), Smart Service Welt (2020), Solarplaza (2019) **Interviews** 16, 22, 24, 31, 32, 33, 34, 37, 38, 39, 40, 45
E-roaming	**Literature** Al-Obaidi et al. (2021), Andoni et al. (2019), Bhushan et al. (2020), Christidis et al. (2021), Christidis et al. (2021), Fu et al. (2020), Hasankhani et al. (2021), Khorasany et al. (2021), Lei et al. (2021), Nour et al. (2022), Soto et al. (2021), Thukral (2021), Tushar et al. (2021), Zhang et al. (2018), Zhang et al. (2022) **Reports** Accenture (2018), BNetzA (2019), Council on Foreign Relations (2018), DENA (2019), Detecon (2018), Energy Futures Initiative (2018), FFE (2018), Germanwatch (2018), IRENA (2019), NERA (2019), SAP (2018) **Interviews** 1, 9, 12, 13, 25, 32, 33, 34, 43
Labeling of electricity	**Literature** Ahl et al. (2019), Ahl et al. (2020), Andoni et al. (2019), Di Silvestre et al. (2019), Fu et al. (2020), Howson (2019), Hua et al. (2020), Lei et al. (2021), Mika et al. (2021), Nour et al. (2022), Wang et al. (2020) **Reports** Bundesblock (2019), CLI (2019), Council on Foreign Relations (2018), European Commission (2019), FFE (2018), FSR (2019), GIZ Mexico (2019), NERA (2019), SAP (2018), Smart Service Welt (2020), Stanford (2019) **Interviews** 3, 4, 7, 26, 28, 29, 31, 34, 35, 36, 37, 39, 40, 41, 45
Certificate trading	**Literature** Ahl et al. (2019), Ahl et al. (2020), Andoni et al. (2019), Di Silvestre et al. (2019), Fu et al. (2020), Howson (2019), Hua et al. (2020), Lei et al. (2021), Mika et al. (2021), Nour et al. (2022), Wang et al. (2020) **Reports** Accenture (2018), BNetzA (2019), Capgemini (2019), CLI (2019), Cognizant (2018), Congressional Research Service (2019), DENA (2019), Energy Futures Initiative (2018), EnergyWeb (2019): EU Blockchain Observatory and Forum (2019), EY (2019), FFE (2018), FSR (2019), GIZ Mexico (2019), IRENA (2019), NERA (2019), Netherlands Innovation Network (2019), Smart Service Welt (2020), Stanford (2019) **Interviews** 1, 3, 5, 7, 10, 15, 31, 35, 36, 37, 39, 45
Machine identities	**Literature** Hirsch et al. (2018), Li et al. (2019), Ante et al. (2021) **Reports** enisa (2022), Fraunhofer FIT (2021), UTCID Report (2021), Bitkom (2020), EU Blockchain Observatory and Forum (2019) **Interviews** 41, 42, 43, 44, 45

References

[1] Jensen T, Hedman J, Henningsson S. How TradeLens delivers business value with blockchain technology. MIS Q Exec 2019;18:221–43. https://doi.org/10.17705/2msqe.00018.

[2] Jović M, Tijan E, Žgaljić D, Aksentijević S. Improving maritime transport sustainability using blockchain-based information exchange. Sustainability 2020;12:1–19. https://doi.org/10.3390/su12218866.

[3] Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C. Designing microgrid energy markets: A case study: The Brooklyn Microgrid. Appl Energy 2018;210:870–80. https://doi.org/10.1016/j.apenergy.2017.06.054.

[4] Lüth A, Zepter JM, Crespo del Granado P, Egging R. Local electricity market designs for peer-to-peer trading: The role of battery flexibility. Appl Energy 2018;229:1233–43. https://doi.org/10.1016/j.apenergy.2018.08.004.

[5] Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, et al. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renew Sustain Energy Rev 2019;100:143–74. https://doi.org/10.1016/j.rser.2018.10.014.

[6] Di Silvestre ML, Gallo P, Guerrero JM, Musca R, Riva Sanseverino E, Sciumè G, et al. Blockchain for power systems: Current trends and future applications. Renew Sustain Energy Rev 2020;119:109585. https://doi.org/10.1016/j.rser.2019.109585.

[7] Baumgarte F, Glenk G, Rieger A. Business models and profitability of energy storage. IScience 2020;23:101554. https://doi.org/10.1016/j.isci.2020.101554.

[8] Lin J, Pipattanasomporn M, Rahman S. Comparative analysis of auction mechanisms and bidding strategies for P2P solar transactive energy markets. Appl Energy 2019;255:113687. https://doi.org/10.1016/j.apenergy.2019.113687.

[9] Accenture. Blockchain for utilities: Beyond the Buzz. 2018.

[10] de Vries A. Bitcoin's energy consumption is underestimated: A market dynamics approach. Energy Res Soc Sci 2020;70:101721.

[11] Stoll C, Klaaßen L, Gallersdörfer U. The carbon footprint of bitcoin. Joule 2019;3(7):1647–61. https://doi.org/10.1016/j.joule.2019.05.012.

[12] Rieger A, Roth T, Sedlmeir J, Fridgen G. We need a broader debate on the sustainability of blockchain. Joule 2022;6(6):1137–41. https://doi.org/10.1016/j.joule.2022.04.013.

[13] Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C. Designing microgrid energy markets: A case study: The Brooklyn Microgrid. Appl Energy 2018;210:870–80. https://doi.org/10.1016/j.apenergy.2017.06.054.

[14] Choobineh M, Arab A, Khodaei A, Paaso A. Energy innovations through blockchain: Challenges, opportunities, and the road ahead. Electr J 2022;35:107059. https://doi.org/10.1016/j.tej.2021.107059.

[15] Akter MN, Mahmud MA, Haque ME, Oo AM. An optimal distributed energy management scheme for solving transactive energy sharing problems in residential microgrids. Appl Energy 2020;270:115133. https://doi.org/10.1016/j.apenergy.2020.115133.

[16] Zhang W, Wei C-P, Jiang Q, Peng C-H, Zhao JL. Beyond the block: A novel blockchain-based technical model for long-term care insurance. J Manag Inf Syst 2021;38(2):374–400. https://doi.org/10.1080/07421222.2021.1912926.

[17] Bian Z, Zhang Q. Combined compromise solution and blockchain-based structure for optimal scheduling of renewable-based microgrids: Stochastic information approach. Sustain Cities Soc 2022;76:103441. https://doi.org/10.1016/j.scs.2021.103441.

[18] Lei N, Masanet E, Koomey J. Best practices for analyzing the direct energy use of blockchain technology systems: Review and policy recommendations. Energy Policy 2021;156:112422. https://doi.org/10.1016/j.enpol.2021.112422.

[19] Ahl A, Yarime M, Goto M, Chopra SS, Kumar NM, Tanaka K, et al. Exploring blockchain for the energy transition: Opportunities and challenges based on a case study in Japan. Renew Sustain Energy Rev 2020;117:109488. https://doi.org/10.1016/j.rser.2019.109488.

[20] Mika B, Goudz A. Blockchain-technology in the energy industry: blockchain as a driver of the energy revolution? With focus on the situation in Germany. Energy Syst 2021;12(2):285–355. https://doi.org/10.1007/s12667-020-00391-y.

[21] Wang L, Liu J, Yuan R, Wu J, Zhang D, Zhang Y, et al. Adaptive bidding strategy for real-time energy management in multi-energy market enhanced by blockchain. Appl Energy 2020;279:115866. https://doi.org/10.1016/j.apenergy.2020.115866.

[22] Ante L, Steinmetz F, Fiedler I. Blockchain and energy: A bibliometric analysis and review. Renew Sustain Energy Rev 2021;137:110597. https://doi.org/10.1016/j.rser.2020.110597.

[23] Hirsch A, Parag Y, Guerrero J. Microgrids: A review of technologies, key drivers, and outstanding issues. Renew Sustain Energy Rev 2018;90:402–11. https://doi.org/10.1016/j.rser.2018.03.040.

[24] Bischi A, Basile M, Poli D, Vallati C, Miliani F, Caposciutti G, et al. Enabling low-voltage, peer-to-peer, quasi-real-time electricity markets through consortium blockchains. Appl Energy 2021;288:116365. https://doi.org/10.1016/j.apenergy.2020.116365.

[25] Tushar W, Yuen C, Saha TK, Morstyn T, Chapman AC, Alam MJE, et al. Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges. Appl Energy 2021;282:116131. https://doi.org/10.1016/j.apenergy.2020.116131.

[26] Sedlmeir J, Buhl HU, Fridgen G, Keller R. The Energy Consumption of Blockchain Technology: Beyond Myth. Bus Inf Syst Eng 2020;62:599–608. https://doi.org/10.1007/s12599-020-00656-x.

[27] Li Y, Yang W, He P, Chen C, Wang X. Design and management of a distributed hybrid energy system through smart contract and blockchain. Appl Energy 2019;248:390–405. https://doi.org/10.1016/j.apenergy.2019.04.132.

[28] Roth T, Stohr A, Amend J, Fridgen G, Rieger A. Blockchain as a driving force for federalism: A theory of cross-organizational task-technology fit. Int J Inf Manage 2022:102476. https://doi.org/10.1016/j.ijinfomgt.2022.102476.

[29] Zhang H, Wang J, Ding Y. Blockchain-based decentralized and secure keyless signature scheme for smart grid. Energy 2019;180:955–67. https://doi.org/10.1016/j.energy.2019.05.127.

[30] Mahmoudian EM. A hierarchical blockchain-based electricity market framework for energy transactions in a security-constrained cluster of microgrids. Int J Electr Power Energy Syst 2022;139:108011. https://doi.org/10.1016/j.ijepes.2022.108011.

[31] Crosby M, Pattanayak P, Verma S, Kalyanaraman V. Blockchain technology: Beyond bitcoin Appl Innov 2016;2:71.

[32] Wüst K, Gervais A. Do you need a blockchain? 2018 Crypto Val. Conf. Blockchain Technol., IEEE; 2018, p. 45–54.

[33] Bhushan B, Khamparia A, Sagayam KM, Sharma SK, Ahad MA, Debnath NC. Blockchain for smart cities: A review of architectures, integration trends and future research directions. Sustain Cities Soc 2020;61:102360. https://doi.org/10.1016/j.scs.2020.102360.

[34] Christidis K, Sikeridis D, Wang Y, Devetsikiotis M. A framework for designing and evaluating realistic blockchain-based local energy markets. Appl Energy 2021;281:115963. https://doi.org/10.1016/j.apenergy.2020.115963.

[35] Esmat A, de Vos M, Ghiassi-Farrokhfal Y, Palensky P, Epema D. A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. Appl Energy 2021;282:116123. https://doi.org/10.1016/j.apenergy.2020.116123.

[36] Watanabe, H., Fujimura, S., Nakadaira, A., Miyazaki, Y., Akutsu, A., Kishigami, J., Blockchain contract: Securing a blockchain applied to smart contracts. 2016 IEEE Int Conf Consum Electron ICCE 2016 2016:467–8. 10.1109/ICCE.2016.7430693.

[37] Chen S, Shen Z, Zhang L, Yan Z, Li C, Zhang N, et al. A trusted energy trading framework by marrying blockchain and optimization. Adv Appl Energy 2021;2:100029. https://doi.org/10.1016/j.adapen.2021.100029.

[38] Butijn B-J, Tamburri DA, Heuvel W-J. Blockchains: A Systematic Multivocal Literature Review. ACM Comput Surv 2021;53(3):1–37.

[39] Körner M-F, Sedlmeir J, Weibelzahl M, Fridgen G, Heine M, Neumann C. Systemic risks in electricity systems: A perspective on the potential of digital technologies. Energy Policy 2022;164:112901. https://doi.org/10.1016/j.enpol.2022.112901.

[40] Thomas L, Zhou Y, Long C, Wu J, Jenkins N. A general form of smart contract for decentralized energy systems management. Nat Energy 2019;4:140–9. https://doi.org/10.1038/s41560-018-0317-7.

[41] Zhang T, Pota H, Chu CC, Gadh R. Real-time renewable energy incentive system for electric vehicles using prioritization and cryptocurrency. Appl Energy 2018;226:582–94. https://doi.org/10.1016/j.apenergy.2018.06.025.

[42] Wu Y, Wu Y, Guerrero JM, Vasquez JC. Digitalization and decentralization driving transactive energy Internet: Key technologies and infrastructures. Int J Electr Power Energy Syst 2021;126:106593. https://doi.org/10.1016/j.ijepes.2020.106593.

[43] Kitchenham B. Procedures for performing systematic reviews. Keele, UK, Keele Univ 2004;33:1–26.

[44] Moher D. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann Intern Med 2009;151(4):264.

[45] Orlikowski WJ, Baroudi JJ. Studying Information Technology in Organizations: Research Approaches and Assumptions. Inf Syst Res 1991;2:1–28. https://doi.org/10.1287/isre.2.1.1.

[46] Corbin JM, Strauss A. Grounded theory research: Procedures, canons, and evaluative criteria. Qual Sociol 1990;13:3–21. https://doi.org/10.1007/BF00988593.

[47] Starr MA. Qualitative and mixed-methods research in economics: surprising growth, promising future. J Econ Surv 2014;28(2):238–64. https://doi.org/10.1111/joes.12004.

[48] Hesse-Biber SN, Johnson RB, editors. The Oxford Handbook of Multimethod and Mixed Methods Research Inquiry. Oxford University Press; 2015.

[49] Cohen J. Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit. Psychol Bull 1968;70:213–20. https://doi.org/10.1037/h0026256.

[50] Wolf R. Rating scales. J Keeves (Ed), Educ Res Methodol Meas an Int Handb 1997:958–965.

[51] Schneiders A, Shipworth D. Community energy groups: Can they shield consumers from the risks of using blockchain for peer-to-peer energy trading? Energies 2021;14(12):3569. https://doi.org/10.3390/en14123569.

[52] Noor S, Yang W, Guo M, van Dam KH, Wang X. Energy Demand Side Management within micro-grid networks enhanced by blockchain. Appl Energy 2018;228:1385–98. https://doi.org/10.1016/j.apenergy.2018.07.012.

[53] Jiang Y, Zhou K, Lu X, Yang S. Electricity trading pricing among prosumers with game theory-based model in energy blockchain environment. Appl Energy 2020;271:115239. https://doi.org/10.1016/j.apenergy.2020.115239.

[54] Mengelkamp E, Schlund D, Weinhardt C. Development and real-world application of a taxonomy for business models in local energy markets. Appl Energy 2019;256:113913. https://doi.org/10.1016/j.apenergy.2019.113913.

[55] Ableitner L, Tiefenbeck V, Meeuw A, Wörner A, Fleisch E, Wortmann F. User behavior in a real-world peer-to-peer electricity market. Appl Energy 2020;270:115061. https://doi.org/10.1016/j.apenergy.2020.115061.

[56] Guerrero J, Gebbran D, Mhanna S, Chapman AC, Verbič G. Towards a transactive energy system for integration of distributed energy resources: Home energy management, distributed optimal power flow, and peer-to-peer energy trading. Renew Sustain Energy Rev 2020;132:110000. https://doi.org/10.1016/j.rser.2020.110000.

[57] Hoess A, Roth T, Sedlmeir J, Fridgen G, Rieger A. With or without blockchain?: Towards a decentralized, SSI-based eRoaming architecture. Proc Hawaii Int Conf Syst Sci 2022, 2022.:4621–30. https://doi.org/10.24251/hicss.2022.562.

[58] Kirli D, Couraud B, Robu V, Salgado-Bravo M, Norbu S, Andoni M, et al. Smart contracts in energy systems: A systematic review of fundamental approaches and implementations. Renew Sustain Energy Rev 2022;158:112013. https://doi.org/10.1016/j.rser.2021.112013.

[59] Morstyn T, Farrell N, Darby SJ, McCulloch MD. Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nat Energy 2018;3:94–101. https://doi.org/10.1038/s41560-017-0075-y.

[60] Sousa T, Soares T, Pinson P, Moret F, Baroche T, Sorin E. Peer-to-peer and community-based markets: A comprehensive review. Renew Sustain Energy Rev 2019;104:367–78. https://doi.org/10.1016/j.rser.2019.01.036.

[61] Alt R, Wende E. Blockchain technology in energy markets – An interview with the European energy exchange. Electron Mark 2020;30(2):325–30. https://doi.org/10.1007/s12525-020-00423-6.

[62] German Energy Agency. DENA: Blockchain in the integrated energy transition. Dena Multi-stakeholder Study 2018:84.

[63] Chanson M, Bogner A, Bilgeri D, Fleisch E, Wortmann F. Blockchain for the IoT: privacy-preserving protection of sensor data. J Assoc Inf Syst 2019:1272–307. https://doi.org/10.17705/1jais.00567.

[64] Mehdinejad M, Shayanfar H, Mohammadi-Ivatloo B. Peer-to-peer decentralized energy trading framework for retailers and prosumers. Appl Energy 2022;308:118310. https://doi.org/10.1016/j.apenergy.2021.118310.

[65] An J, Lee M, Yeom S, Hong T. Determining the Peer-to-Peer electricity trading price and strategy for energy prosumers and consumers within a microgrid. Appl Energy 2020;261:114335. https://doi.org/10.1016/j.apenergy.2019.114335.

[66] Neves D, Scott I, Silva CA. Peer-to-peer energy trading potential: An assessment for the residential sector under different technology and tariff availabilities. Energy 2020;205:118023. https://doi.org/10.1016/j.energy.2020.118023.

[67] Imani MH, Ghadi MJ, Ghavidel S, Li L. Demand response modeling in microgrid operation: a review and application for incentive-based and time-based programs. Renew Sustain Energy Rev 2018;94:486–99. https://doi.org/10.1016/j.rser.2018.06.017.

[68] Gao H, Xu S, Liu Y, Wang L, Xiang Y, Liu J. Decentralized optimal operation model for cooperative microgrids considering renewable energy uncertainties. Appl Energy 2020;262:114579. https://doi.org/10.1016/j.apenergy.2020.114579.

[69] Yang J, Dai J, Gooi HB, Nguyen HD, Wang P. Hierarchical Blockchain Design for Distributed Control and Energy Trading Within Microgrids. IEEE Trans Smart Grid 2022;13:3133–44. https://doi.org/10.1109/TSG.2022.3153693.

[70] Yang J, Dai J, Gooi HB, Nguyen H, Paudel A. A Proof-of-Authority Blockchain Based Distributed Control System for Islanded Microgrids. IEEE Trans Ind Informatics 2022;1. https://doi.org/10.1109/TII.2022.3142755.

[71] Hasankhani A, Mehdi Hakimi S, Bisheh-Niasar M, Shafie-khah M, Asadolahi H. Blockchain technology in the future smart grids: A comprehensive review and frameworks. Int J Electr Power Energy Syst 2021;129:106811. https://doi.org/10.1016/j.ijepes.2021.106811.

[72] Perrons RK, Cosby T. Applying blockchain in the geoenergy domain: The road to interoperability and standards. Appl Energy 2020;262:114545. https://doi.org/10.1016/j.apenergy.2020.114545.

[73] Utz M, Johanning S, Roth T, Bruckner T, Strüker J. From ambivalence to trust: Using blockchain in customer loyalty programs. Int J Inf Manage 2022:102496. https://doi.org/10.1016/j.ijinfomgt.2022.102496.

[74] Luke MN, Anstey G, Taylor W, Sirak A. Blockchains in Power Markets. Decentralized Disruption or Incremental Innovation? 2019.

[75] Amend J, Fridgen G, Rieger A, Roth T, Stohr A. The evolution of an architectural paradigm-using blockchain to build a cross-organizational enterprise service bus. 54th Hawaii Int Conf Syst Sci (HICSS), Maui, Hawaii 2021.

[76] Beck R, Müller-Bloch C, King JL. Governance in the blockchain economy: A framework and research agenda. J Assoc Inf Syst 2018:1020–34.

[77] Hawlitschek F, Notheisen B, Teubner T. The limits of trust-free systems: A literature review on blockchain technology and trust in the sharing economy. Electron Commer Res Appl 2018;29:50–63. https://doi.org/10.1016/j.elerap.2018.03.005.

[78] Ahl A, Yarime M, Tanaka K, Sagawa D. Review of blockchain-based distributed energy: Implications for institutional development. Renew Sustain Energy Rev 2019;107:200–11. https://doi.org/10.1016/j.rser.2019.03.002.

[79] Diniz EH, Yamaguchi JA, dos Santos TR, de Carvalho AP, Alego AS, Carvalho M. Greening inventories: Blockchain to improve the GHG Protocol Program in scope 2. J Clean Prod 2021;291:125900. https://doi.org/10.1016/j.jclepro.2021.125900.

[80] Fernando Y, Rozuar NHM, Mergeresa F. The blockchain-enabled technology and carbon performance: Insights from early adopters. Technol Soc 2021;64:101507. https://doi.org/10.1016/j.techsoc.2020.101507.

[81] Khorasany M, Dorri A, Razzaghi R, Jurdak R. Lightweight blockchain framework for location-aware peer-to-peer energy trading. Int J Electr Power Energy Syst 2021;127:106610. https://doi.org/10.1016/j.ijepes.2020.106610.

[82] Abad AV, Dodds PE. Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. Energy Policy 2020;138:111300. https://doi.org/10.1016/j.enpol.2020.111300.

[83] Li W, Wang L, Li Ye, Liu Bo. A blockchain-based emissions trading system for the road transport sector: policy design and evaluation. Clim Policy 2021;21(3): 337–52. https://doi.org/10.1080/14693062.2020.1851641.

[84] Houtan B, Hafid AS, Makrakis D. A survey on blockchain-based self-sovereign patient identity in healthcare. IEEE Access 2020;8:90478–94. https://doi.org/10.1109/ACCESS.2020.2994090.

[85] Bandara E, Liang X, Foytik P, Shetty S, Hall C, Bowden D, et al. A blockchain empowered and privacy preserving digital contact tracing platform. Inf Process Manag 2021;58:102572. https://doi.org/10.1016/j.ipm.2021.102572.

[86] Ehrlich T, Richter D, Meisel M, Anke J. Self-sovereign identity as the basis for universally applicable digital identities. HMD Prax Der Wirtschaftsinformatik 2021;58:247–70. https://doi.org/10.1365/s40702-021-00711-5.

[87] Anania L, Le GG, van Kranenburg R. Disposable identities? Why digital identity matters to blockchain disintermediation and for society. Disintermediation Econ., Springer 2021:297–327. https://doi.org/10.1007/978-3-030-65781-9_14.

[88] Alam SM, Al MMA, Hossain MS, Samiruzzaman M. A novel approach to manage ownership and VAT using blockchain-based digital identity. Int Symp Ubiquitous Netw., Springer 2021:255–68. https://doi.org/10.1007/978-3-030-86356-2_21.

[89] Sedlmeir J, Smethurst R, Rieger A, Fridgen G. Digital identities and verifiable credentials. Bus Inf Syst Eng 2021;63(5):603–13. https://doi.org/10.1007/s12599-021-00722-y.

[90] Lacity M, Carmel E. Implementing Self-Sovereign Identity (SSI) for a Digital Staff Passport at UK National Health Service (NHS) 2022.

[91] Sikorski JJ, Haughton J, Kraft M. Blockchain technology in the chemical industry: Machine-to-machine electricity market. Appl Energy 2017;195:234–46. https://doi.org/10.1016/j.apenergy.2017.03.039.

[92] Foti M, Vavalis M. Blockchain based uniform price double auctions for energy markets. Appl Energy 2019;254:113604. https://doi.org/10.1016/j.apenergy.2019.113604.

[93] Luo F, Dong ZY, Liang G, Murata J, Xu Z. A Distributed Electricity Trading System in Active Distribution Networks Based on Multi-Agent Coalition and Blockchain. IEEE Trans Power Syst 2019;34:4097–108. https://doi.org/10.1109/TPWRS.2018.2876612.

[94] Zimmermann H, Hoppe J. Blockchain-Opportunities and threats for the energy transition. Germanwatch 2018.

[95] Diestelmeier L. Changing power: Shifting the role of electricity consumers with blockchain technology – Policy implications for EU electricity law. Energy Policy 2019;128:189–96. https://doi.org/10.1016/j.enpol.2018.12.065.

[96] Lowitzsch J, Hoicka CE, van Tulder FJ. Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future? Renew Sustain Energy Rev 2020;122:109489. https://doi.org/10.1016/j.rser.2019.109489.

[97] Sedlmeir J, Ross P, Luckow A, Lockl J, Miehle D, Fridgen G. The DLPS: A new framework for benchmarking blockchains. Proc 54th Hawaii Int Conf Syst Sci 2021:6855–64. https://doi.org/10.24251/hicss.2021.822.

[98] de Vries A. Renewable Energy Will Not Solve Bitcoin's Sustainability Problem. Joule 2019;3:893–8. https://doi.org/10.1016/j.joule.2019.02.007.

[99] Rieger A, Roth T, Sedlmeir J, Weigl L, Fridgen G. Not yet another digital identity. Nat Hum Behav 2022;6:3. 10.1038/s41562-021-01243-0.

[100] Rieger A, Lockl J, Urbach N, Guggenmos F, Fridgen G. Building a blockchain application that complies with the EU general data protection regulation. MIS Q Exec 2019;18:263–79. https://doi.org/10.17705/2msqe.00020.

[101] Sedlmeir J, Lautenschlager J, Fridgen G, Urbach N. The transparency challenge of blockchain in organizations. Electron Mark 2022. https://doi.org/10.1007/s12525-022-00536-0.

[102] Toufaily E, Zalan T, Dhaou SB. A framework of blockchain technology adoption: An investigation of challenges and expected value. Inf Manag 2021;58(3):103444. https://doi.org/10.1016/j.im.2021.103444.

[103] van Leeuwen G, AlSkaif T, Gibescu M, van Sark W. An integrated blockchain-based energy management platform with bilateral trading for microgrid communities. Appl Energy 2020;263:114613. https://doi.org/10.1016/j.apenergy.2020.114613.

[104] Zia MF, Elbouchikhi E, Benbouzid M. Microgrids energy management systems: A critical review on methods, solutions, and prospects. Appl Energy 2018;222: 1033–55. https://doi.org/10.1016/j.apenergy.2018.04.103.

[105] García Vera YE, Dufo-López R, Bernal-Agustín JL. Energy management in Microgrids with Renewable Energy Sources: A Literature Review. Appl Sci 2019;9 (18):3854. https://doi.org/10.3390/app9183854.

[106] Rieger A, Thummert R, Fridgen G, Kahlen M, Ketter W. Estimating the benefits of cooperation in a residential microgrid: A data-driven approach. Appl Energy 2016;180:130–41. https://doi.org/10.1016/j.apenergy.2016.07.105.

[107] Sedlmeir J, Völter F, Strüker J. The next stage of green electricity labeling: using zero-knowledge proofs for blockchain-based certificates of origin and use. ACM SIGENERGY Energy Informatics Rev 2021;1(1):20–31. https://doi.org/10.1145/3508467.3508470.

[108] Equigy. A multi-TSO initiative to catalyse the cost-effective use of balancing potential provided by flexible distributed energy resources. 2020.

[109] Fu Z, Dong P, Ju Y. An intelligent electric vehicle charging system for new energy companies based on consortium blockchain. J Clean Prod 2020;261:121219. https://doi.org/10.1016/j.jclepro.2020.121219.

[110] Acharya S, Mieth R, Karri R, Dvorkin Y. False data injection attacks on data markets for electric vehicle charging stations. Adv Appl Energy 2022;7:100098. 10.1016/j.adapen.2022.100098.

[111] Politou E, Alepis E, Patsakis C. Forgetting personal data and revoking consent under the GDPR: Challenges and proposed solutions. J Cybersecur 2018;4. https://doi.org/10.1093/cybsec/tyy001.

[112] Strüker J, Schellinger B, Völter F, Wohlleben J. InDEED Forschungsprojekt untersucht den Einsatz von Blockchain im Energiesektor 2022.

[113] Fraunhofer Institute for Industrial Engineering IAO. Smart Energy Communities Smart Services für die dezentrale Energiewirtschaft der Zukunft 2022.

[114] Carbonfuture. Carbon Removal you can trust. 2022.

[115] Richard P, Mamel S. Blockchain machine identity ledger. Future Energy Lab 2022.

[116] Energy Web Foundation. EWF and Elia Group Self-Sovereign-Identity (SSI) Wallet Components 2022.

[117] MiCA. Proposal for a Regulation of the European Parliament and of the Council on Markets in Crypto-assets, and amending Directive (EU) 2019/1937 2020;593 final:1–167.

[118] European Commission. Regulation of the European Parliament and of the council - amending Regulation (EU) No 910/2014 as regards establishing a framework for a European Digital Identity 2021.

[119] Gourisetti SNG, Sebastian-Cardenas DJ, Bhattarai B, Wang P, Widergren S, Borkum M, et al. Blockchain smart contract reference framework and program logic architecture for transactive energy systems. Appl Energy 2021;304:117860. https://doi.org/10.1016/j.apenergy.2021.117860.

[120] Garrido GM, Sedlmeir J, Uludağ Ö, Alaoui IS, Luckow A, Matthes F. Revealing the landscape of privacy-enhancing technologies in the context of data markets for the IoT: A systematic literature review. J. Netw. Comput. Appl. 2022:103465. https://doi.org/10.1016/j.jnca.2022.103465.

[121] Sedlmeir J, Wagner T, Djerekarov E, Green R, Klepsch J, Rao S. A serverless distributed ledger for enterprises. Proc 55th Hawaii Int Conf Syst Sci 2021: 7382–91. https://doi.org/10.24251/hicss.2022.886.