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Review article

A comprehensive academic and industrial survey of blockchain technology for the energy sector using fuzzy Einstein decision-making

Umit Cali [a,b,*], Annabelle Lee [c], Berry Hayes [d], Claudio Lima [e], D. Jonathan Sebastian-Cardenas [f], David Flynn [g], Emre Kantar [h], Farrokh Rahimi [i], Kaung Si Thu [j], Marco Pasetti [k], Marthe Fogstad Dynge [b], Merlinda Andoni [g], Muhammet Deveci [l,m,n], Murat Kuzlu [o], Raquel Alanso [h], Kim-Kwang Raymond Choo [p], Sambeet Mishra [q], Shammya Shananda Saha [r], Sonam Norbu [g], Srinikhil Gourisetti [s], Ugur Halden [b], Vahid Hosseinezhad [d], Valentin Robu [t]

[a] School of Physics, Engineering and Technology, University of York, Heslington, York, YO10 5DD, UK
[b] Norwegian University of Science and Technology, Elektro E/F, E427, Gløshaugen, O. S. Bragstads plass 2e, Norway
[c] Nevermore Security, 31256 Stone Canyon Rd Unit 209 Evergreen, CO, 80439-9695, United States
[d] University College Cork, College Road, Cork, Ireland
[e] Microbrains AI, Houston, TX, United States
[f] PNNL, 902 Battelle Blvd, Richland, WA 99354, United States
[g] University of Glascow, Glasgow G12 8QQ, United Kingdom
[h] Sintef Energi AS, Sem Sælands vei 11, 7034 Trondheim, Norway
[i] Open Access Technology International, 7901 Computer Ave, Bloomington, MN 55435, United States
[j] Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand
[k] University of Brescia, Piazza del Mercato, 15, 25121 Brescia BS, Italy
[l] Department of Industrial Engineering, Turkish Naval Academy, National Defence University, 34942 Tuzla, Istanbul, Türkiye
[m] Department of Computer Science and Engineering, College of Informatics, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea
[n] Department of Information Technologies, Western Caspian University, Baku 1001, Azerbaijan
[o] Old Dominion University, 5115 Hampton Blvd, Norfolk, VA 23529, United States
[p] University of Texas at San Antonio, 1 UTSA Circle, San Antonio, TX 78249, United States
[q] University of South Eastern Norway, Lærerskoleveien 40, 3679 Notodden, Norway
[r] Electric Power Research Institute, 3420 Hillview Ave, Palo Alto, CA 94304, United States
[s] Google, 1600 Amphitheatre Parkway in Mountain View, CA, United States
[t] Centrum Wiskunde & Informatica, Science Park 123, 1098 XG Amsterdam, Netherlands

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ABSTRACT

The global energy sector is undergoing a significant transformation driven by decarbonization and digitalization, leading to the emergence of Distributed Ledger Technology (DLT) — particularly blockchain — as a promising tool for enhancing transparency, security, and efficiency in modern power systems. This study aims to provide a comprehensive academic and industrial survey of blockchain applications in the energy sector and develop a robust decision-making framework to identify and prioritize the most promising real-world use cases based on multidisciplinary criteria. A three-stage methodology was adopted: (i) a literature and market review encompassing over 300 academic publications and commercial blockchain initiatives in energy, (ii) an in-depth

* Corresponding author at: Norwegian University of Science and Technology, Elektro E/F, E427, Gløshaugen, O. S. Bragstads plass 2e, Norway.

E-mail addresses: umit.cali@york.ac.uk (U. Cali), ablee@nevermoresecurity.com (A. Lee), barry.hayes@ucc.ie (B. Hayes), crlima100@gmail.com (C. Lima), d.sebastiancardenas@pnnl.gov (D.J. Sebastian-Cardenas), David.Flynn@glasgow.ac.uk (D. Flynn), emre.kantar@sintef.no (E. Kantar), farrokh.rahimi@oati.net (F. Rahimi), a.kaungsithu@outlook.com (K.S. Thu), marco.pasetti@unibs.it (M. Pasetti), marthe.f.dynge@ntnu.no (M.F. Dynge), Merlinda.Andoni@glasgow.ac.uk (M. Andoni), muhammetdeveci@gmail.com (M. Deveci), mkuzlu@odu.edu (M. Kuzlu), raquel.alonso@sintef.no (R. Alanso), raymond.choo@fulbrightmail.org (K.-K.R. Choo), sambeet.mishra@usn.no (S. Mishra), sssaha@lbl.gov (S.S. Saha), sonam.norbu@glasgow.ac.uk (S. Norbu), srigourisetti@google.com (S. Gourisetti), ugur.halden@ife.no (U. Halden), v.h.nezhad@ugmail.com (V. Hosseinezhad), v.robu@cwi.nl (V. Robu).

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evaluation of the evolution and viability of blockchain initiatives in energy with the help of expert surveys, and (iii) a novel decision-making model using a q-rung orthopair fuzzy Multi-Attributive Border Approximation (q-ROF-MABAC) method under the Einstein operator. The results were compared with existing decision models to validate consistency and robustness. Nine key blockchain use case categories were identified and ranked based on technical, economic, and governance dimensions. The results demonstrated that integrating expert insights into a fuzzy logic framework helps filter out overhyped claims in the literature and prioritize realistic and high-impact applications such as green certificates, grid services, and peer-to-peer energy trading. The model's rankings remained stable across varying weight configurations, confirming the robustness of the methodology. This study provides an evidence-based decision-support tool for researchers, industry stakeholders, and policymakers to better understand, evaluate, and adopt blockchain technologies in the energy sector.

Contents

1. Introduction

Modern power systems and their associated landscapes are evolving swiftly, propelled by trends such as decarbonization and digitalization. These forces drive the twin energy transition, referred to as the *digital-green shift*, which in turn has a profound impact on society [1].

As the penetration of Distributed Energy Resources (DERs) increases, power system operators have realized that the conventional operation and management of power systems is becoming inadequate. Particular concerns arise from the penetration of intermittent and difficult-to-predict Renewable Energy Sources (RESs) and from the growing complexity of the energy landscape. The increasing presence of energy prosumers and the transition toward dynamic and deregulated systems are introducing new players and sophisticated business models, further contributing to operational, management, and security issues [2–4].

Among various approaches proposed by academia and industry to support this paradigm shift, the use of DLT as one of the enablers of the digital green shift in power systems is emerging as a promising solution. DLTs are becoming increasingly popular in a wide range of applications, ranging from healthcare to supply chain, manufacturing, finance, energy, telecommunications, and others [5–8]. More recently, numerous studies and review articles have been published addressing the use of DLT in the field of power and energy systems. Indeed, integrating DLTs into power systems has already demonstrated its ability to enhance security, transparency, and trust among participants and entities by securely storing information in distributed databases [9,10]. DLTs can potentially transform the energy trading landscape between regional grids and microgrids, enabling direct and secure transactions among prosumers, consumers, producers, and service providers. This would also empower local energy communities, optimize resource utilization, and set the stage for a more flexible and resilient energy future [11–13].

The authors in [14] provide a comprehensive review of DLT for Peer-to-Peer (P2P) energy trading in local energy markets and propose a transactive energy management infrastructure considering a Virtual Power Plant (VPP) aggregator and residential prosumers along with a novel consensus protocol.

The study in [15] provides a comprehensive analysis identifying the impact of several factors (market, regulation, transaction characteristics, security, and interoperability) on the implementation of different DLTs in energy use cases for decision-makers in electric utilities and government administrations. The study uses qualitative data obtained through in-depth interviews with 22 experts from the energy sector, blockchain enterprises, and research institutions. The study in [16] also uses expert elicitation and qualitative content analysis based on semi-structured interviews with blockchain experts in Germany to shed light on the challenges and opportunities of DLTs in energy applications. The authors provide insights by a thorough cross-domain discussion around technological, economic, social, environmental, and institutional aspects.

The study in [17] provides a detailed analysis regarding the main advantages and limitations of DLT with technical challenges in energy systems in terms of energy generation, P2P energy markets, green certificate registries, etc. It also provides suggestions and guidelines for implementing DLT in different categories of use cases in the energy sector.

Meanwhile, the authors in [18] propose a blockchain architecture for several smart grid applications, such as home automation, smart cities, microgrids, Electric Vehicles (EVs), synchrophasors, energy management systems, and advanced metering infrastructure, and discuss challenges and solutions for blockchain adoption.

The article in [19] focuses on DLT applications for DER management and integration. The paper discusses various use cases, including using blockchains for communication purposes at individual houses, collaborative settings (e.g., local energy communities), aggregators, VPPs, and fully decentralized systems (e.g., P2P trading). The study in [20] also focuses on blockchain adoption for distributed generation applications.

The authors in [21] describe the transactive energy concept in detail and propose a decentralized transactive energy system architecture formed by seven functional layers, namely: user layer (L1), network layer (L2), system operator layer (L3), market layer (L4), distributed ledger layer (L5), communication layer (L6), and regulation layer (L7). The proposed architecture is also compared with a practical case study of the Brooklyn microgrid in terms of key performance parameters, such as hash-chain structure, scalability, energy use, transaction fee, latency, popularity, and security. According to this study, additional emulation and simulation tools are required to evaluate the challenges of transactive energy system implementation and learn how to mitigate system failures. In addition, the authors in [22] propose incentive mechanisms that can be used for energy producers and consumers in local energy markets using DLT by policymakers. It also provides a detailed analysis of market pricing and parameters of the German energy market to demonstrate the proposed energy policy instruments for the DLT-based local energy market. Similarly, the authors in [23] focus on pricing mechanisms in applications of blockchain technologies in the energy sector.

The study in [24] reviews use cases for blockchains in the energy sector but also focuses on technical features of blockchain technologies that may lead to high energy consumption, such as different consensus mechanisms. A comprehensive and systematic analysis and classification of blockchain consensus approaches is presented in [25]. The authors provide a detailed analysis of the advantages, disadvantages, and emerging trade-offs of each approach.

Cybersecurity aspects of the DLT applications have been investigated by a number of studies. The study in [26] focused on vulnerabilities of DLT software components used in energy use cases and provided a cyber risk and resilience model analysis. The study in [27] presented in detail the security risks of smart grid applications and implications for blockchain adoption. Finally, a review paper summarizing and discussing findings from other review papers published in the literature can be found in [28].

These are only a few examples of the growing number of studies in the scientific literature dealing with applying DLT to the power and energy sector. Despite this substantial body of research, the authors believe that the literature still lacks a comprehensive and structured review of actual DLT applications in the energy sector. The actual refers to the normalized in terms of overly hyped use and application of the technology.

To fill this gap, this study proposes a structured survey of real industrial applications by reviewing emerging start-up companies operating within this field, in addition to academic outcomes and studies. A three-fold stage framework has been designed to identify the most promising energy DLT use cases by sorting them in terms of importance. The first stage consists of a comprehensive literature and market survey of start-up companies, projects, and academic studies in energy DLT, ranked based on the number of occurrences. However, since this simple ranking mechanism could provide misleading results due to the inability to determine the impact and success of the investigated use cases, a second evaluation stage has been adopted. The second stage approach is based on a DM algorithm supported by expert opinion via academic and industry surveys. A q-ROF [29] based Multi-Attributive Border Approximation (MABAC) [30] under fuzzy Einstein operator is proposed to prioritize the energy blockchain use cases among nine use cases as alternatives. Flexibility is achieved in the fusion and information processing process by applying the Einstein operator in a fuzzy environment, while q-ROF sets are used thanks to their ability to choose the power rating and to consider expert opinions. After the DM algorithm is applied, the outcomes of the survey and the DM algorithm are analyzed and discussed to draw the conclusions of the study. Lastly, the authors reflected their expert opinions to interpret

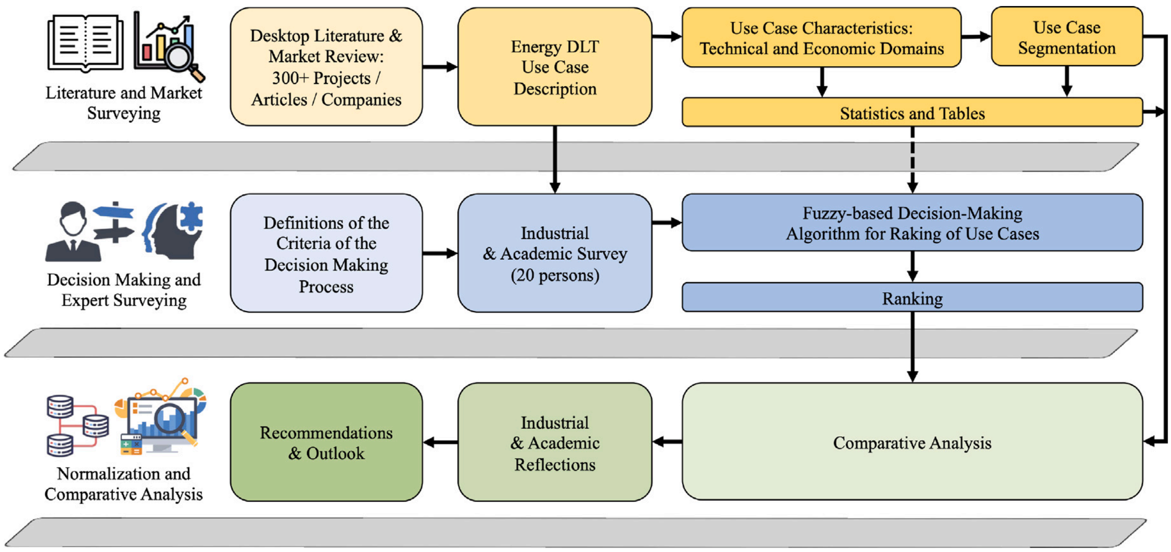

Fig. 1. Map of the methodology and process flow of the study.

the outcomes and provide some suggestions for academia, industry, and policymakers.

The motivation for this study stems from the urgent need to address the convergence of decarbonization and digitalization in the evolving energy landscape. As energy systems transition toward decentralization, automation, and increased participation of prosumers, ensuring trust, transparency, and operational security becomes increasingly critical. DLTs, particularly blockchain, have emerged as promising enablers of these objectives by facilitating peer-to-peer trading, renewable certification, automated settlements, and secure data management. However, despite the growing body of academic literature and the proliferation of pilot projects, a structured and evidence-based evaluation of blockchain applications in the energy sector remains lacking. This gap has resulted in difficulty distinguishing between high-impact, feasible use cases and speculative or overhyped implementations. Our study aims to bridge this gap by integrating academic insights, industrial trends, and expert knowledge to provide a realistic, multidimensional prioritization of blockchain energy use cases. This work is further informed by the authors' active engagement in international standardization bodies, including IEEE SA P2418.5, and collaborations with global stakeholders, which underline this research's practical and policy relevance.

To summarize, the main contributions of this study include:

(i) a comprehensive survey focusing on real-world industrial and academic applications, encompassing a review of both start-up companies and research outcomes and studies;
(ii) an investigation on company initiatives based on blockchain technology, exploring what happened to them over the years and providing valuable insights into the dynamic landscape of blockchain adoption in the power and energy industry;
(iii) the development of a novel DM approach to evaluate and rank a set of existing energy use cases using blockchain technology, thereby contributing to the advancement of DM frameworks in the power and energy sector and normalizing the outcomes of straight forward literature surveys.

The rest of the paper is organized as follows. Section 2 provides an overview of the proposed research methodology, while Section 3 covers the essential background materials on DLT. In Section 4, an extensive exploration of blockchain-based use cases in the energy sector is presented, emphasizing their economic, technological, and governance structures. This section presents the results of the literature and market survey (i.e., the first stage of the evaluation framework). In Section 5, the Fuzzy Einstein-based DM approach (i.e., the second stage of the evaluation framework) is described in detail, and its results are presented. In Section 6, the survey outcomes and the DM algorithm are analyzed and discussed to draw the quantitative and qualitative conclusions of the review. Finally, in Section 7, the concluding remarks of the study are provided by summarizing its key findings and insights.

2. Methodology

As illustrated in the diagram of Fig. 1, the methodology employed in this study comprises three layers: (1) Literature and market surveying, (2) DM and expert surveying, and (3) Normalization and comparative analysis, respectively. The primary goal of the proposed framework is to identify the most realistic and feasible energy use scenarios where DLT can be applied. The selection of high-potential energy DLT use cases necessitates a comprehensive study that takes into account various aspects, including energy, politics, law, technology, economic implications, and environmental challenges.

The initial step in the framework involves conducting a comprehensive literature study, complemented by a detailed market survey. This step focuses on gaining insights into the current state-of-the-art expertise in energy DLT use case studies and DM.

The outcomes obtained from a previous study provide crucial inputs to our innovative DM algorithm using expert surveying. This method has seven separate DM criteria (C1–C7). To guarantee a comprehensive and authoritative examination, we have enlisted individuals from the relevant sector. These expert views serve as intermediaries, contributing to the DM algorithm and so aiding in the creation of a prioritized list of the nine alternative energy DLT use cases.

The last step involves an in-depth comparative analysis, including viewpoints from both academia and industry. This not only gives a thorough comparison but also makes suggestions covering technical, economic, technological, and energy policy aspects, providing a forward-thinking perspective.

3. Foundations of distributed ledger technology

DLT can be defined as an aggregating term for distributed databases across multiple users at different locations. The most well-known and heavily utilized version of DLT is blockchain technology, where information is stored in "blocks", which then connect to each other via cryptographic hash functions. Hash functions are one-way cryptographic functions which satisfy the following properties:

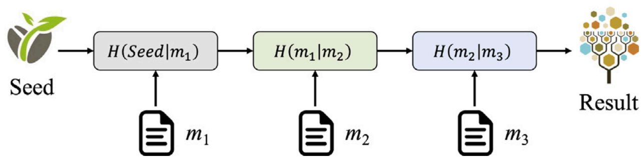

Fig. 2. Utilization of hash chains in DLT.

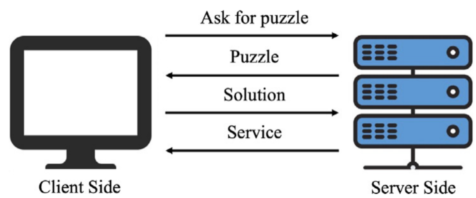

Fig. 3. Puzzle steps between a client and a server.

Efficiency: For any given message m_1, it should be computationally quick to compute hash $H(m_1)$;

Pre-image resistance: Recovering the message m_1 from the hash of the message $H(m_1)$ should be computationally infeasible;

Second pre-image resistance: Given the message m_1 and the hash of the message $H(m_1)$, no other message as m_2 should exist which will satisfy $H(m_1) = H(m_2)$;

Collision resistance: It should be computationally infeasible to find two messages as m_1 and m_2, which will allow $H(m_1) = H(m_2)$.

Due to the properties of hash functions mentioned earlier, a hash chain link can provide a tamper-proof construction since any change in messages (m_1, m_2, m_3) without affecting the result will cause a hash collision. This is schematically represented in Fig. 2.

3.1. Access control and consensus mechanisms

The availability of access control is a relevant characteristic of blockchain technology. In general, there are five categories, namely permissioned, permissionless, public, private, and hybrid access control. Public blockchains, as the name suggests, allow any individual to participate in maintaining and governing the blockchain, whereas private blockchains allow only a selected number of participants with prior approval. Meanwhile, the difference between permissioned and permissionless access control can be explained by the availability of anonymity. If blockchain participants can set up their accounts and perform transactions without an off-chain identity, such as a public key certificate, it can be said that blockchain technology is permissionless. Lastly, hybrid access control generally offers an amalgamation of public/permissioned combinations where only a selected number of individuals are allowed to maintain the chain while offering public readability.

Blockchain technology relies on honest nodes and different consensus mechanisms to ensure integrity. Consensus mechanisms enable nodes to reach agreements on extending the blockchain, determining block rewards, including transaction fees, and resolving conflicts. As shown in Fig. 3, Proof-of-Work (PoW) consensus mechanism depends on solving computational "puzzles" which can be defined as a moderately difficult problem, i.e., hard enough that it affects the computation performance when repeated many times but easy enough that solving one puzzle does not affect the performance [31].

First applications of puzzles focused on Denial-of-Service (DoS) attack resistance and spam email deterrence [32], where second-generation applications focused on PoW concept for achieving consensus in blockchain technology. While puzzle properties can vary based on their specific application fields, some key properties can be identified as follows:

Unforgeability Puzzles should only be generated by the intended servers or software, ensuring that unauthorized entities cannot create valid puzzles.

Parallelizability Multiple computers, such as mining pools, should be capable of solving puzzles in less time collectively compared to a single computer, allowing for increased efficiency.

Tuneability The difficulty level of puzzles should be adjustable, allowing for adaptation to changing network conditions or computational resources.

Usefulness The work performed in solving a puzzle should have practical value or serve a purpose beyond the consensus mechanism itself.

There are two primary drawbacks to the PoW consensus mechanism. Firstly, it leads to the wastage of energy if the computational power required for solving hashes is not utilized for any other productive purpose. Recent estimates indicate that during the year 2019 the Bitcoin network, the largest cryptocurrency network which rely on PoW, consumed an amount of electrical energy of more than 87 TWh, equivalent to that of a country such as Belgium [33]. The second drawback is that PoW can be categorized under 51% attacks, which can easily happen in a blockchain with a small number of miners [34]. If a miner manages to achieve more than 50% of all the available computational power across the blockchain, then they can prevent other miners from verifying the blocks and capitalize on block rewards.

Proof-of-Stake (PoS) is an alternative consensus mechanism that was designed to address the drawbacks of PoW by avoiding wasteful mining and providing extra security against 51% attacks while also reducing the inter-block times. The consensus for selecting the next block in PoS is achieved through a process where nodes are randomly chosen, and the probability of selection is determined by their stake in the blockchain. The main idea of PoS is based on the nodes with significant investments in the blockchain having a strong incentive to maintain the accuracy and integrity of the chain. Therefore, PoS can be defined as a type of virtual mining where nodes purchase stakes instead of mining hardware and electricity. Later on, the consensus algorithm distributes the power according to the number of stakes each miner holds. On the other hand, one of the drawbacks of the PoS consensus mechanism is Nothing-at-Stake (NaS) problem [35]. Producing new blocks in a pure PoS-type blockchain has a negligible cost, and the nodes can extend one or more chains with different valid blocks. If each node can keep the fork alive for a few blocks, then they might be able to offload the value on one fork for another cryptocurrency and keep the same value on the other fork. This type of attack is not a concern in blockchain technologies that employ the PoW consensus mechanism, as creating forks in such blockchains entails significant computational expenses. A solution to the NaS problem can be the use of the combination of PoS and PoW as a hybrid consensus mechanism, where participants still need to solve puzzles but can reduce their difficulty by using their individual stakes [36].

Another relevant consensus mechanism is the so-called Byzantine consensus, where a group of nodes collaborates to select a periodically chosen leader based on majority agreement for the purpose of choosing and validating the next block. This consensus mechanism remains actively researched and is currently utilized by several blockchain technologies like Hyperledger Fabric [37].

The development and validation of consensus mechanisms for emerging blockchain technologies continue to be an active field of research, and it is expected that more consensus mechanisms will be developed and implemented in the future [38,39].

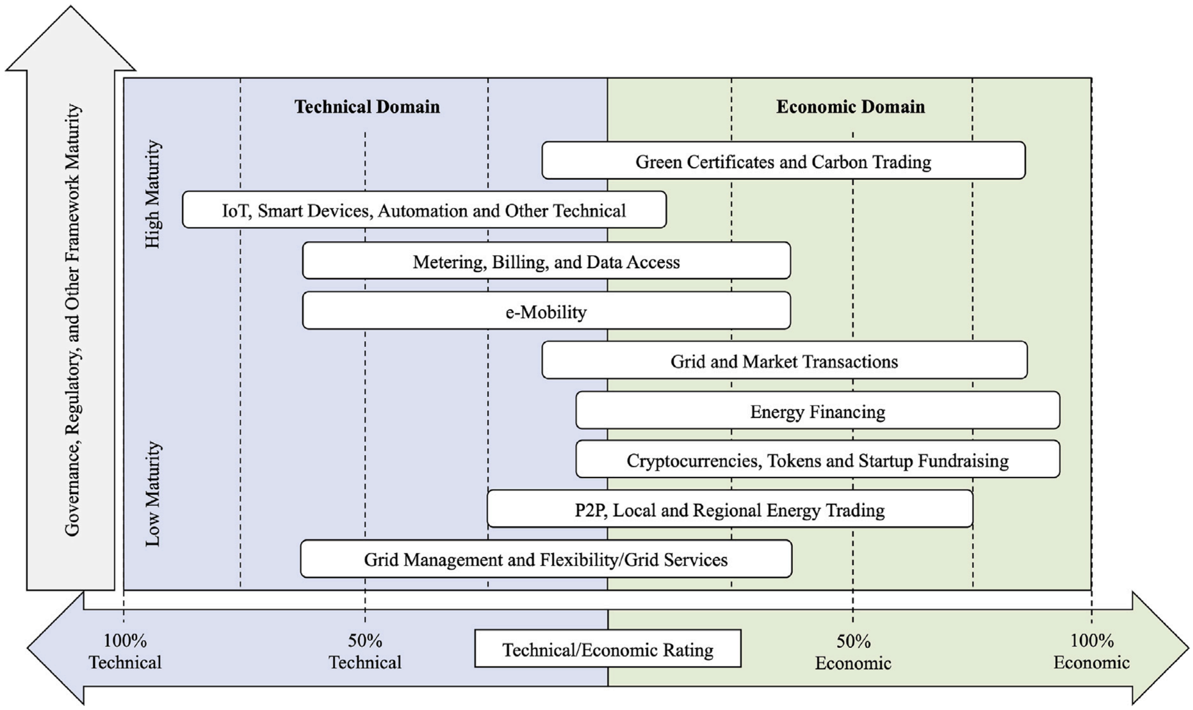

Fig. 4. Energy DLT use case classification.

3.2. Smart contracts

Initial applications of DLT technology were mainly focused on the development of cryptocurrencies, which can act as an alternative medium of exchange for goods and services. The second-generation applications focused on providing data storage via online ledgers, while the third generation of DLT applications can be defined as the availability of smart contracts for distributed computing.

Smart contracts automatically execute programs when the stated arguments in the contracts are met [40]. The support for smart contracts can be implemented into public, private, or hybrid type DLT mechanisms as long as they support Pay-to-Script-Hash (P2SH) type of transactions. As of 2023, DLT platforms, including Ethereum, Hyper Ledger Fabric, Corda, Stellar, NEM, IOTA, and Waves, have supported smart contracts. Furthermore, it is likely that more DLTs will start to offer support for smart contracts [40,41].

Smart contracts within the DLT can autonomously execute settlements based on predetermined timeframes and energy consumption patterns. Timestamps in each transaction create an unalterable audit trail, offering instant visibility to all network nodes. This guarantees adherence to the time-of-use plan, facilitating timely settlements and preventing disputes or delays [42]. The current applications of smart contracts focus on P2P energy trading [40] and crowdfunding [43,44]. However, in addition to P2P energy trading and crowdfunding, smart contracts are increasingly being utilized in supply chain management, where they ensure that the goods are tracked from production to delivery phases, automating payments upon successful delivery and preventing disputes through verifiable and immutable record keeping [45]. This is particularly beneficial as the global supply chains are becoming increasingly complex and decentralized with multiple participating agents, ensuring that every transaction, process and trade is recorded accurately and transparently.

Furthermore, smart contracts are paving the way toward decentralized an autonomous organizations, where the governance rules are embedded into the code and thus, require no human or Trusted Third Parties (TTP) intervention. This has profound implications for sectors such as healthcare, finance and insurance where administrative tasks can be automated, reducing human error and thus, improving efficiency. For example, in the healthcare domain, smart contracts can securely store and manage patient health data, ensuring privacy while enabling authorized personnel to access medical records only when pre-determined conditions are met [46]. Within the insurance domain, smart contracts can automate the process of claims and trigger automated payouts when the pre-determined conditions are met, which can reduce delays and ensure fairness [47]. As seen in the literature, the use cases for smart contracts are extensive, making DLT and smart contracts a critical component of next generation digitalization processes.

4. Energy DLT landscape

In this section, we draw our attention to DLT applications for the energy sector. To date, many classifications have been proposed to examine applications of DLT systems. In this study, the classification depicted in Fig. 4 is adopted. This classification is based on the evaluation of nine groups of use cases, rated by their technical vs. economic nature, and by their maturity with respect to governance, regulatory, and other related frameworks. First, the evaluation metrics for the proposed classification are defined, by also introducing the explored use cases. Then, companies and initiatives are presented as relevant examples for the considered use cases.

DLT systems can be broadly classified into three categories, namely: economic, technology, and governance structure.

Economic covers all the cases that involve financial transactions. The economic category can be further expanded into seven subcategories containing: carbon trading, green certificates, energy financing, metering and billing, P2P energy trading, grid transactions, and cryptocurrencies & token investment.

Technology covers all the cases that are focused on a specific technology. This category can be expanded to electrical Mobility (e-Mobility), IoT, smart devices & automation, privacy, security, and reliability & grid management.

Governance structure explains the ownership structure of an initiative. This measure covers new participants, non-partisan or non-profit, national conglomerates, and multi-national conglomerates.

Some applications sit at the intersection of multiple categories. Energy financing, for instance, can be mapped into all three categories. Additionally, some categories are, in fact, linked to each other, while some are agnostic toward other categories and denote stand-alone applications. Thus, in order to reflect these multi-category use cases, use cases in Fig. 4 are represented across the three different categories by assigning a weight to their degree of relevance and/or maturity related to each individual category.

4.1. Cybersecurity in DLT

Prior to an in-depth technical analysis of the DLT-based energy use cases, it is noteworthy to mention that cybersecure deployment of DLT is pivotal to the cyber-resilience and fault tolerant operation of the use cases. Since the boom of DLT-based energy use cases, much of the focus has been on use cases and tabletop exercises. To advance those engineering and scientific experiments to long-term scalable, interoperable, and cyber secure real-world use cases with 100,000 or more operational nodes, technical standards are required to ensure such a process.

Incorporating DLT into client systems can create a nuanced interplay of cybersecurity risks and political concerns. The decentralized nature of DLT, distributing data control, poses vulnerabilities if clients lack strong cybersecurity measures. Malicious actors may exploit these weaknesses to manipulate ledger data, potentially leading to politically sensitive events or exposing sensitive user behavior. This underscores the essential requirement for robust cybersecurity protocols during DLT integration to safeguard data integrity and mitigate the risk of politically charged breaches [48].

The IEEE P2418.5 blockchain for energy working group's cybersecurity task force designed and published the DLT cybersecurity stack and mapped the seven-layer technology stack to multiple energy use cases to demonstrate the secure use of DLT for energy applications [49]. In addition to a technology stack presented by the IEEE working group, the Sunspec working group developed a blockchain-based method to record private keys for DER applications [50]. Evaluating the security from the lens of evaluating the security of the network of energy systems that uses DLT for any application, researchers tailored the NIST Cybersecurity Framework and demonstrated a codified method to use it for DLT-based application and system security assessment and vulnerability analysis [51]. In another similar work [52], the authors addressed more of a fundamental question - "does the use case truly benefit from DLT?" that should be considered as a precursor study prior to seriously considering DLT as a value-added solution for DLT applications. Another set of research explorations involving permissioned/private blockchain attempted to address fundamental grid resiliency questions and supply chain regulatory use cases [51] when DLTs are involved as integrated technologies for the grid and energy applications [53,54].

4.2. Energy DLT use cases

In the following section, the energy DLT use cases considered by the present study are introduced by grouping them into the following nine categories:

1. Green Certificates and Carbon Trading;
2. IoT, Smart Devices, Automation, and Other Technical;
3. Metering, Billing, and Data Access;
4. e-Mobility;
5. Grid and Market Transactions;
6. Energy Financing;
7. Cryptocurrencies, Tokens and Startup Fundraising;
8. P2P, Local and Regional Energy Trading;
9. Grid Management and Flexibility/Grid Services.

4.2.1. Green certificates and carbon trading

DERs offer an excellent opportunity for a sustainable generation that will aid in the transition toward decentralized, efficient, and green energy generation. It is envisioned that distributed generation presents numerous advantages over traditional centralized generation, such as reduced transmission losses, increased efficiency, and greater security, owing to the improved and flexible DER and storage systems [55]. Local generation might be offered by an individual (i.e., residential, commercial, or industrial) or by a group of users and prosumers forming a community or a coalition able to work as an entity to either supply (local energy sharing) or provide different ancillary services (load sharing, energy aggregation, etc.) [56]. Distributed energy, despite being a promising solution to globally accelerate the energy transition, is still limited to only a small fraction of the total energy generation and use worldwide. Several regulatory, economic, social, and technical issues persist, deterring the large-scale implementation of DER [57]. Therefore, the adoption of DER is still a challenge to overcome.

The increase of the share of renewable energy generation requires multiple actions, including the active participation of final customers, contributing as distributed producers (e.g., with Photovoltaic (PV) roof-top installations), or as responsible consumers. Indeed, energy providers already offer electricity supply contracts that guarantee that all the energy supplied to the end user is 100% renewable. However, the electricity generated either from renewables or conventional resources is combined on the shared electricity grid, and therefore, specific mechanisms are required to ensure that the electricity provided to a specific customer is entirely generated by RES. To cope with this issue, different regulatory frameworks have been independently developed at the national level by many countries, defining specific mechanisms able to measure, track, and certify the exchange of renewable energy in power grids. The most widespread mechanism involves the issuance of so-called Green Certificates (GCs). Also referred to as Renewable Energy Certificates (RECs), GCs are assets that can be earned by both producers and energy providers that certify the amount or green energy produced (and delivered) to the grid and sold to final customers, respectively [58]. Worth to note, GCs can be earned by producers following the actual production of electrical energy from renewable energy sources, or bought from GCs trading platforms to satisfy desired/required rates of green energy production. This not only encourages consumers to adopt renewable generations but also helps the renewable energy market to grow.

Each GC represents a certain amount of electricity produced and delivered to the grid by a renewable source. Typically, for every unit of energy produced, the renewable generation owner generates a GC that they can either keep or sell [59]. Any consumer who buys the GC gains ownership of the green power and can claim that the energy being used originates from a renewable source. GCs are a currency of the renewable energy market and a credible way to buy and sell renewable electricity. GCs are issued and traded in the compliance market because of either government policies or voluntarily to avail incentives [60]. GC prices are dependent on several factors, e.g., location, level of supply and demand, the frequency of certificate generation, scarcity, etc. Thus, GC are limited in the market and, once sold, cannot be transferred to others. Certificate markets have been established in China (NRIC, CREEI), the European Union (EEX, AIB), India (RECRI, IEX), and the United States (WREGIS, WECC) [61–66]. The typical structure of TGC markets is depicted in Fig. 5.

Despite the potential advantages of tradable certificate markets, GCs have lost popularity due to the small market size, being inefficient and unfavorable, and may require a proper enforcement mechanism to

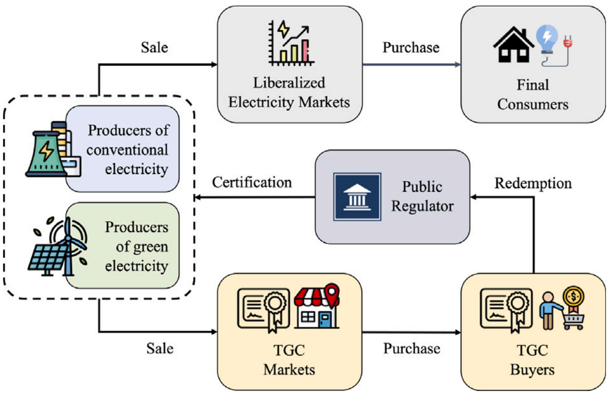

Fig. 5. Typical TGC markets, adapted from [67].

survive [68]. In this regard, DLT technology offers an excellent opportunity to promote the GC market in a decentralized fashion. DLT for GC trading can overcome several issues, subsequently improving robustness, transparency, security, and verifiability, while minimizing corruption in certificate acquisition or use. Although studies dealing with the application of DLT to GC markets are in their early stages, a few of them present a huge potential. As seen in [69], Blockchain DLT significantly increases consumer engagement and market efficiency when compared to traditional approaches. Also, Proof-of-Generation (PoG) consensus [57] is found to be more efficient and scalable compared to PoW and PoS protocols. The study in [70] presented a blockchain-based decentralized market for the trading of power, carbon, and green certificates. A different blockchain structure/chain is realized for each market, which may include different technical features, transaction types, and consensus algorithms. Coordination between the different chains is realized with a relay-chain and the use of cross-chain technologies. Initiatives launched by the companies PowerLedger [71] and Foton-Energy Web [72] are aimed to reduce transaction costs, track renewable energy, and automatize the GC market to fully decentralize the process.

The establishment of the GC market is one way to promote green and clean energy, but mere renewable energy usage does not allow a completely sustainable solution to the issue of increased emissions of greenhouse gases. Despite the addition of 260 GW capacity of renewable energy in 2020, with an increase of about 50% with respect to 2019 [73], annual global CO_2 emissions are still on the rise [74]. An increase in renewable energy production and a reduction in emissions are two sides of the same coin and, as such, cannot be treated separately. This has led to the emergence of market-based systems aiming to provide economic incentives to reduce emissions. In this context, governments are developing various policies to minimize the environmental footprint, and incentives are provided by both supranational bodies (e.g., the European Union) to local governments, and from the latter to public and private entities.

Carbon emissions trading is a scheme that follows the cap-and-trade government regulatory platform. This caps total carbon emissions and allows organizations to trade their allocation. In such schemes, policymakers calculate the emission caps needed to limit environmental damage. The total maximum carbon allowance computed by that scheme for each country is allocated to the companies based on their historical emission data and traded in the market [75]. Similar to a GC, a Carbon Credit for the emissions of pollutants is equal to one tonne of CO_2. This market also follows the rule of supply and demand and participants can incentivize themselves by signing an agreement to reduce the emissions. The first international carbon market was developed under the UN's 1997 Kyoto Protocol on Climate Change [76]. However, the market suffered several drawbacks, which led to corruption and eventually the collapse of the market. The oldest active carbon market is the European Union's Emission Trading System, which launched in 2005, while other schemes are operating in Canada, Japan, New Zealand, South Korea, Switzerland, and the United States. These markets performed effectively by increasing their value by up to 34% in 2019 [77]. With the traditional structure and cap-and-trade mechanism, the conventional carbon markets are still centralized, with insufficient motivation, inaccuracy, and lack of transparency in emissions data, making them prone to fraud and corruption.

A clean and decentralized cash-credit system based on DLT technology, such as Blockchain, could prevent fraud and corruption by ensuring transparency and making data publicly available. The adoption of DLT would, in fact, facilitate and secure the tracking of carbon credit transactions by leveraging timestamps and unique cryptographic signatures, thus allowing easy detection of frauds of record hacking. As reported in [78], both corporates and individuals can be incentivized by trading in the carbon market. Individuals who may not be very motivated to participate due to a lack of incentives can earn carbon coins through a DLT-based platform and even use them later as an investment.

Several companies, such as EU Scanergy [79], have recognized the potential applications of DLT in carbon trading and are developing projects to successfully implement such schemes. Some have even taken a step further and claimed to launch a fully functional carbon market framework based on DLT. For instance, UPHOLD [80] and XELS [81], both operating on a low-energy Blockchain, aim to enable users to run a full node on a basic laptop without the need for power-intensive mining hardware.

4.2.2. IoT, smart devices, automation, and other technical

The growing diffusion on the market of low-cost smart devices, and high-speed communication networks have led to the advancement of the so-called IoT in various domains. In an IoT environment, multiple smart devices embedded with intelligence, sensors, software, and other technologies are connected and exchange data with other devices and systems over the Internet, forming a collaborative ecosystem. A huge number of IoT-enabled devices and objects have been deployed in electrical networks worldwide [82]. IoT finds its main application in smart device management supporting the very idea of distributed information systems [83].

Thanks to its capability to securely record and maintain data, DLT complements IoT applications at the distribution level. When applied to IoT, as illustrated in the schematic diagram of Fig. 6, DLTs would enable a large number of IoT nodes to securely and confidentially store and exchange information with suppliers or other consumers [83]. Without the application of such schemes, IoT devices and users would create loosely coupled systems that are susceptible to privacy invasion and network attacks, such as Distributed Distributed Denial of Service (DDoD) attacks [84].

Interoperability issues between heterogeneous devices arising from the decentralization of IoT systems can be successfully overcome by implementing composite layers of Blockchains [85]. Thus, with uniform access across the network, various household devices can be converted into Blockchain nodes. This transformation would facilitate the execution of numerous processes by converting and storing IoT data into Blockchains. In this way, DLT technology enables master data management collected through IoT [86].

In the electricity domain, smart devices, such as Smart Meters [87, 88] and Home Energy Management Systems (HEMS) [89–91], serve as gateways for energy-related information flows. With the presence of appropriate communication media, Blockchains could act as supporting technology and manage all data collected through meters, by forming an IoT ecosystem integrated with DLT. This facilitates real-time consumption monitoring, allowing the optimization of energy loads by controlling smart appliances or optimizing intelligent controllers. The

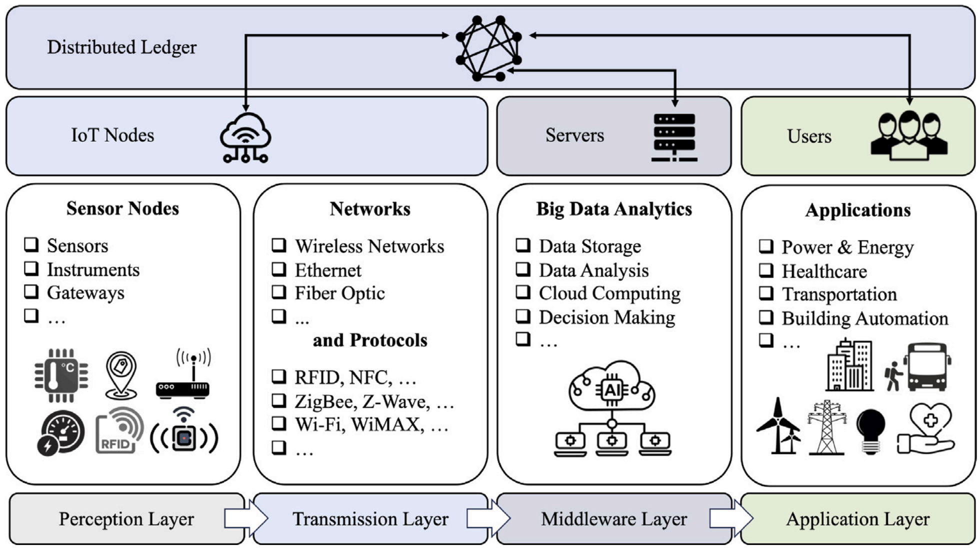

Fig. 6. IoT system with Blockchain technology.

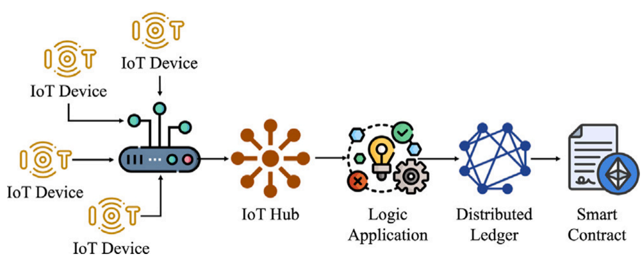

Fig. 7. Typical IoT Blockchain application.

interactions between devices and appliances are automatic, i.e., automatic smart contracts or transactions can be executed with the implementation of DLT technology, thereby reducing a significant amount of cost [92].

Such a system and its use case within the Supply Chain Management (SCM) was presented in [93] where the authors highlighted a comprehensive examination of blockchain technology's role in enhancing SCM. The performed work highlighted a comprehensive examination of blockchain technology's role in enhancing transparency, traceability, efficiency, and security, while addressing significant challenges including high implementation costs, data privacy concerns, and technological immaturity. The study emphasizes blockchain's potential to revolutionize SCM through the utilization of smart contracts and IoT enabled devices, which streamline transactions, reduce fraud, and facilitate real-time data sharing across stakeholders. However, the researchers mention that despite its' promise, widespread adoption is hindered by skepticism and a lack of standardization, which further speculates more research is needed within such applications of DLT.

Fig. 7 shows a simple schematic diagram of an IoT ecosystem integrated with DLT: data gathered in a gateway, transferred to an IoT hub, processed in logic applications, and finally transferred to DLT section for saving in the ledger and trigger a smart contract if the conditions are satisfied. IoT ecosystems integrated with DLT offer the ability to identify and verify data anywhere and anytime. They provide an opportunity to consumers as well as suppliers and retailers with traceable services [13] to work on smart management. DLT facilitates consumer access to the power markets and enables consumers to track the origin of energy.

Consumer-owned assets, such as solar PV generation units at the premises, tracking of green energy generation or consumption, batteries in EVs participating in the local market, smart meters, creation of digital coins or carbon credits, value certificates, etc., can be successfully managed by Blockchain-IoT solutions (Dajie, BitFury, Filament, ElectriCChain-SolarCoin, Slock.it, PowerLedger) [94,95]. It is believed that such smart asset management systems improve the commercial value of assets owned, build customer confidence, and develop trust among different parties. This can also include Artificial Intelligence (AI) and Machine Learning (ML), as well as Machine-to-Machine (M2M) networking applications for industrial or other types of automation processes. In this application, data gathering and storage combined with cybersecurity applications such as secure credential transfer or edge-to-cloud data security are used. VERV [96], E7ventures [97] are two sample initiatives. VERV can develop an AI-based IoT hub, which can sample data 5 million times faster than smart meters, and thanks to implemented blockchain technology, it forms the basis for their P2P energy trading system [98]. Also, E7ventures can provide investment services for all ranges of smart systems, including smart cities and buildings, IoT-mobility and fog computing with software systems such as AI, ML, P2P, and M2M Networking, Cybersecurity, and Cryptocurrency and Blockchain technology.

As mentioned earlier, the adoption of enabler technologies such as IoT and DLT is increasing, driven by the rise of smart homes, high RES integration, and consequently, smart grids [99,100]. Therefore, the integration of IoT with DLT is an active area of research. An example of such integration is presented in [101], where researchers propose Direct Current (DC) powered edge devices that automatically check smart contract states depending on energy generation from PVs, executing transactions accordingly. Meanwhile, in [102], researchers focus on an AI-based intrusion detection and privacy protection system based on DLT-enabled IoT networks for smart cities. Validation results showed that as the number of users increases, the system performs better at intrusion detection. A similar study [103] focused on accuracy and needed computational power. According to the results, performing intrusion detection in near real-time big data with enablers such as IoT and DLT could yield accuracies up to 90%, depending on the algorithms, edge devices, and network configuration.

However, the energy and computational consumptions of these systems pose a major challenge, potentially addressable by the utilization of Hybrid-DLT(H-Chain) [104] or task offloading algorithms, as discussed in [105]. The paper [106] adopts a smart contract approach using Hyperledger Fabric and focuses on the security aspects of Blockchains for industrial IoT applications. Additionally, [107] addresses privacy leakage in energy DLT-enabled IoT systems. The authors propose a Proof-of-Concept (PoC) based on homomorphic encryption, limiting participant information in the case of data leaks without affecting the Transactions per Second (TPS) values of the DLT. Another approach to providing anonymity during data transfer within smart grids is proposed by [108], where an additional interface added to security gateways is utilized to provide advanced anonymity independent of the communication protocols used. In the event of an attack on the system itself via intrusions, [109] proposes switching the system away from DLT smart contracts and device updates upon detection.

Privacy is also an important aspect for the healthcare sector, that is why the research performed in [110], proposed a novel and a hybrid Multi Criteria Decision Making (MCDM) approach, combining Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Multi Criteria Optimization and Compromise Solution (MCOCS) under an Intuitionistic Fuzzy Set (IFS) environment to evaluate blockchain networks in healthcare. The method introduces a new logarithmic distance measure to handle data uncertainty, and utilizes the rank-sum model to assess the importance of decision makers and criteria. Applied to a case study, the model identifies "Integration of IoT and Blockchain" as the optimal network for healthcare applications based on the selected five key criteria by the authors.

A similar study was presented by Pathak et al. [111], where a novel MCDM framework was presented for evaluating hospitals that implement blockchain technology. The model combines Interval Valued q-Rung Orthopair Fuzzy (IVq-ROF) interaction aggregation operators, a standard deviation-based objective weighting method, and the Pivot Pairwise Relative Criteria Importance Assessment (PIPRECIA) technique for subjective weights, culminating in a Weighted Aggregated Sum Product Assessment (WASPAS) based ranking system. Applied to a real-world case study in Kolkata, India, the study identified "flexibility", "scalability", "transaction speed", and "accountability" as the most critical factors in assessing blockchain-enabled hospitals. Although the focus is on healthcare sector, the study's emphasis on blockchain integration into digital hospital infrastructure, which involves data collection, processing, and management in a decentralized environment. Thus, directly relates to smart, connected systems.

As more people move toward cities across the world, the energy utilization of buildings increasingly become a critical research area. Therefore, the researchers in [112] developed a blockchain-based system to manage the data storage and communications across various sensors and smart meters in buildings. By leveraging the blockchain's transparency and security features, the model aims to improve data sharing among key stakeholders, thereby allowing easier overview of building energy key indexes. The authors of the study evaluated the developed system through a case study and demonstrated its potential to enhance project outcomes and support sustainable development in the construction sector.

4.2.3. Metering, billing, and data access

Information sharing is a pillar in the electricity sector; being aware of the consumption patterns of individual users is paramount for grid operators and the electricity market. Therefore, transparency and security in information sharing is one of the most important concerns in this frame, even more so when considering new market environments with small producers and prosumers. Questions are to be addressed in terms of data storage, transfer, and creation [113,114]:

- Who is the owner of customer data?
- Who regulates the use and access of customer data?
- How is privacy and security of customer data guaranteed?
- Who will benefit and under what terms from the sale or transfer of customer data if it is allowed?
- Will competing electricity providers be allowed to have similar access to customer data as the utility?

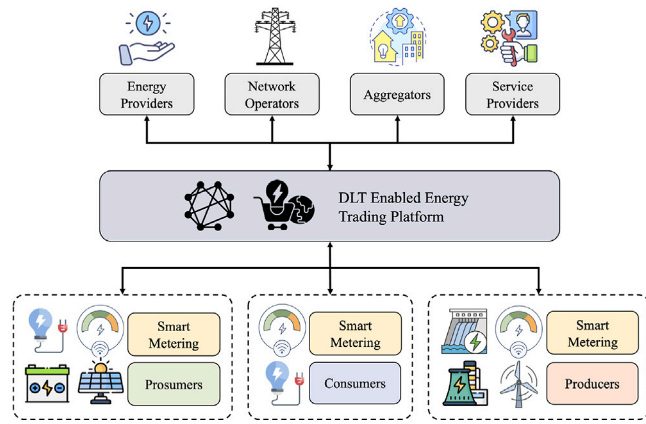

Fig. 8. Metering blockchain applications.

A participant in the electricity market, even if not actively participating, has the responsibility to provide information constantly to the utility, service provider, and grid operator. This is possible through a Smart Meter, a device capable of measuring energy intake/production, current, voltage, power factor, etc. The information provided by a participant in the form of a transaction must be stored. Decentralizing the storage makes the process resistant to communication dropouts and cyber-attacks [14,115]. DLT is itself a decentralized storage scheme, improving data immutability, information accessibility, and security [116,117]. After the data is stored securely, it can be accessed for billing purposes by the relevant party [118]. As illustrated in the schematic diagram of Fig. 8, the possibilities for metering, data storage, security, and billing applications of DLT are manifold. In particular, the use of a trusted and secure distributed data storage would allow energy providers, aggregators (e.g., energy community operators), or other operators (e.g., service providers offering supervisory energy data analyses) to directly access data from utility smart meters that are currently managed only by network operators [119].

Smart contracts on a DLT platform simplify energy trading through real-time Advanced Metering Infrastructure (AMI) data billing. This automates payments and boosts efficiency, but the reliance on token currency could stall adoption for businesses requiring upfront token investment [120–122]. After data acquisition, in a trading environment, a reliable and efficient information system is expected to be provided by DLT as it offers data consistency and security [123].

The researchers in [124] propose a distributed and encrypted metering technique that is enabled by DLT to allow customers to determine where their data can be used while also ensuring the correctness of the measured data, whereas in [125], the authors are demonstrating a functional Ethereum-based Access Control Contract which enables pseudonymity while also ensuring the system is persistent against single point of failure. Meanwhile, [126] focuses on computational and real-world costs of metering and billing security applications of DLT, where the results indicate that the proposed scenarios and architecture are suitable for smart grid applications.

The research performed in [127] developed an on-chain data storage system with a smart contract written in solidity for energy data storage of various prosumers and the aggregator as the ESS. This was followed by the integration of an optimization based profit distribution algorithm that rewarded each participant within the chain according to their preferences for various Demand Side Management (DSM) applications. According to the results, the blockchain based DSM system was able to achieve 22.63% cost reduction and 48.67% peak demand reduction.

A similar system was also proposed by Meng et al. [128] that works in combination with a Covariance Matrix Adaptation Evolution Strategy (CMA-ES) for optimizing energy trading and management with integrated IoT devices for real time control and data gathering. The performed study demonstrated that such an approach surpassed traditional methods in metrics such as energy efficiency, cost-effectiveness, and cybersecurity. These findings suggest the framework's potential to significantly improve urban energy management, providing a resilient and secure foundation for future smart cities.

However, integration of all these sensors for fast data gathering, as well as the introduction of distributed data storage opens a new cyber domain for attacks toward energy systems [129]. Therefore, researchers in [130] provided an overview of cyberattacks that focuses on distributed data storage on blockchain. According to the findings, cyberattacks such as data spoofing and man in the middle may result in superfluous data generation, invalid data package transmission and introduction of deceptive data. Additionally, they may result in increased network bandwidth usage, memory overflow issues and high latency. Such problems may especially negatively affect real-time event monitoring or demand response applications within blockchain based energy monitoring ecosystem.

4.2.4. e-Mobility

Due to the surging popularity of EVs, the electrification of power systems via high penetration of EVs is becoming a considerable challenge for the system operators and other stakeholders. EVs now play an integral role in shaping the future of energy systems. Despite this, significant barriers to customer adoption persist, with a notable scarcity of public charging infrastructure. Nevertheless, the rise of EVs has also presented valuable opportunities for innovation, with shared mobility and autonomous vehicles representing challenging yet promising developments in this sector. As a result, data management and complex transactions have become essential complements to secure new mobility pathways [131].

EVs introduce a unique dimension to energy trading when compared to traditional stationary DERs, offering opportunities for P2P trading, Demand Response (DR), and Vehicle-to-Grid (V2G) integration. Within DLT platforms, the interaction between EVs and the grid holds the potential to transform energy markets and contribute significantly to a more sustainable future [11–13].

Multiple organizations and companies have explored ways to adopt blockchain to tackle some of the challenges these disruptive innovations pose to mobility. In fact, start-ups believe that a blockchain network can facilitate many small transactions resulting from small power units and do so quickly, securely, and transparently [132]. For example, start-ups MotionWerk [133] and eMotorWerks (rebranded to Enel X) [134] had on a joint pilot project in California to create a marketplace like Airbnb for EV charging. Automatic payments (e.g., for battery charging, toll roads, parking) and intelligent charging schedule for EV batteries are other well-known applications in the transport sector. Fig. 9 shows the potential DLT-based applications in the field of EV and mobility [135].

In [136], a recommendation system for EV charging points was developed based on federated learning and blockchain technology, which allows for increased trust and security. The authors in [137] presented a unified trading mechanism for energy exchanges and the provision of grid flexibility from EVs to aggregators. The authors showed the capability of blockchain technology to facilitate the realization of transactions in a decentralized fashion. However, they noted that scalability and practical implementation depend on the performance of the distributed calculation method adopted.

The work in [138] recently presented a critical analysis of the integration of DLTs in EV environments by proposing an EV charging reference architecture and examining its characteristics and implications from the DLT perspective. The results of the study highlighted that, although DLTs are generally neutral regarding communication with field devices, the specific definition of field communication and protocols significantly influences the design of DLTs, particularly concerning the following aspects:

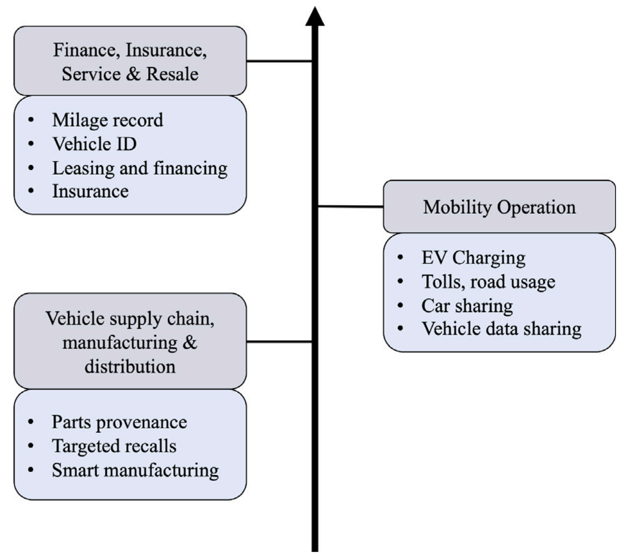

Fig. 9. Potential DLT-based applications for e-Mobility.

- *Standardization*: Multiple competing and non-unified data models may require tailored communication interpreters at the application layer, thus limiting the design of standardized DLT solutions;
- *Interoperability*: control functions defined by protocols may not be uniformly implemented, affecting smart contract implementation. Ambiguity in communication toward end users also poses risks to data privacy and cybersecurity.
- *Cybersecurity*: Internal threats to DLT are independent of the application type. However, external threats from equipment and devices must be carefully evaluated, considering diverse sources susceptible to malicious attacks that could impact DLT execution.

4.2.5. Grid and market transactions

Ranges of other trading programs that, compared to P2P networking, are less radical in terms of decentralization, have recently come under commercial scrutiny and are supported by energy companies. These grid transactions related to the electricity trade in the power system occur in such a way that the power grid remains integrated, even if its form and function change fundamentally. PONTON, for example, has proposed the "Enerchain project" to use blockchain to extend current wholesale electricity markets [139]. In the new market model, transactions can be verified quickly and cheaply. In addition, trading data is transparent to all market participants, enabling more efficient trading. These blockchain-based wholesale markets can expand their derivative market because a blockchain network can handle many smaller transactions that put pressure on a centralized system.

In addition to the wholesale market, blockchain technology can establish the foundation of new ancillary markets that utilize distributed energy sources to help balance the distribution network. Such a case was presented by Alectra [140], where a blockchain exchange platform called GridExchange was developed to provide and record real-time customer data, participation history, and grid needs. Meanwhile, Allgauer Uberlandwerk [141], a regional energy supplier located in Germany, worked with Siemens to develop their own platform under the Pebbles research project [142] that will integrate every participant via blockchain. A similar project, which was called equigy, was also proposed by the Swiss Grid [143], where the main purpose is to reduce short-term fluctuations across four Transmission System Operator (TSO) located in central and south Europe via small distributed sources.

Utilizing these resources not only defers the need for costly infrastructure upgrades to serve local communities but also contributes

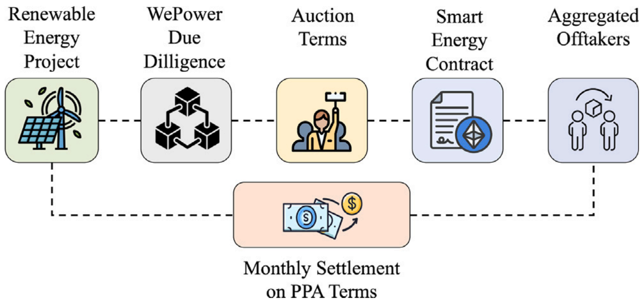

Fig. 10. Renewable energy off-taker contracting solution of WePower, adapted from [150]. PPA: Power Purchase Agreement.

to balancing the overall power grid by stabilizing voltage and frequency [144]. Across various sectors, from South Australia to New York, testing of these markets is underway at the distribution level. In these markets, customers have the ability to buy or sell energy at variable prices based on their location. Given that these markets necessitate a higher volume of transaction processing compared to current wholesale markets, the development of enabling hardware such as smart meters and smart plugs becomes crucial [145]. Therefore, the swift and cost-effective registration of these transactions in a blockchain ledger can lead to transparent and secure transactions.

DLTs, including blockchains, are transforming market design and operation through the Local Exchange Model (LEM) and Regional Exchange Model (REM). These models utilize on-chain and off-chain transactions, enabled by smart contracts, to establish secure and transparent marketplaces. To bolster data protection on end-user devices, market systems, and protocols should capitalize on the inherent security benefits of DLT. [146–149].

4.2.6. Energy financing

Utilizing cryptocurrencies and blockchain to raise capital for energy projects represents a commendable initiative in the energy sector. This classification excludes start-ups that employ Initial Coin Offerings (ICOs) for fundraising, focusing instead on activities primarily centered around using cryptocurrencies to secure funding for projects, particularly in the realm of clean energy. Examples of such endeavors include WePower [150] and ASTRN Energy [151]. These start-up companies leverage the sale of cryptocurrencies to raise capital specifically for renewable energy projects.

In the traditional approach to financing, a majority of funding for a wind or solar project is typically sought through conventional investment methods. However, innovative approaches employed by start-ups like WePower and ASTRN Energy involve funding a portion of the project's budget by selling their own cryptocurrencies, such as WePower currency and ASSETRON tokens, respectively. This enables broader participation in financing new renewable energy projects. Alternatively, a producer may opt to sell a portion of the future green energy production, equivalent to the required capital, through auctioning energy tokens. The proceeds from token sales are recorded and can be used to discount the electricity generated by the project or traded in the market. Fig. 10 illustrates WePower's solution considering a flexible renewable energy contracting option, utilizing Ethereum smart contracts for trading between producers and buyers [150].

DLT networks have the potential to alleviate the challenges faced by renewable energy projects in raising capital. By facilitating the participation of numerous smaller investors in the financing process, these networks can broaden the pool of potential supporters for renewable energy initiatives. In this way, blockchain financing ecosystems empower individuals with smaller financial capacities to invest in projects that might otherwise be inaccessible to them, fostering incentives toward a Sharing Economy (SE).

An example is the Sun Exchange platform, which runs crowd sales for new installations of PVs [152]. This approach enables individuals, regardless of location, to invest in a small share of renewable power generation, typically at schools and smaller enterprises in the developing world. Through immutable records, the investors can track their shares and get income from the electricity produced in the local currency of the project or Bitcoin in the Sun Exchange wallet. The Austrian utility Wien Energie has partnered with the blockchain interface company RIDDLE&CODE to enable micro-investments in PV assets [153,154]. The consumers buy small shares of local PV plants with fiat money and get tokens in return. The tokens can, in turn, be redeemed and used to pay electricity bills.

DLT plays a pivotal role in transforming trade finance, both in local and global markets, by facilitating seamless settlement of diverse currencies, including fiat, digital tokens, and cryptocurrencies. The inherent flexibility of DLT promotes efficient trading across a wider range of assets, extending beyond traditional goods to encompass services, energy, and commodities [155]. However, in the realm of energy financing, the utilization of DLT remains a recent but promising research area, with a primary focus on crowdfunding various RES investments. For instance, the study in [156] found that adopting DLT during the crowdfunding of wind energy investments can decrease the Levelized Cost of Electricity (LCOE) values. This is attributed to the fact that multiple smaller investors, having higher risk tolerance, can offer loans with lower interest rates.

Another noteworthy example comes from the work presented in [43], which introduced a DLT-enabled crowdfunding platform for residential-scale PV projects in Norway. This platform contributed to lowering the LCOE of the projects and achieving grid parity for residential-scale solar energy. Similarly, the study in [44] proposed a PoC based on a DLT-enabled crowdfunding platform, focusing on residential-scale energy storage. The study's results revealed that within the assessed countries, the Levelized Cost of Storage (LCOS) could be reduced by 8 to 20% through the application of DLT-enabled crowdfunding.

Another aspect of the energy financing via DLT tools were focused on by [157], which can result in the further capitalization of the government schemes and increase the promotion of RES. However, [158] specifies that utilization of DLT has been generally limited to borrowing and lending since financing poses incentive problems that are more difficult than simple monetary exchange, such as in the case of economic defaults. In [159], blockchain technology is used to monitor green supply chains. Blockchain monitors enterprises' carbon emissions more efficiently and prevents them from misreporting and greenwashing, which in turn informs financial institutions and retail customers regarding green and sustainable products, leading to improvements in energy financing for renewable projects.

Finally, projects like the Energy Web Foundation (EWF) [160] enable platforms where transaction costs are dynamically adjusted, facilitating frictionless energy delivery. The advantages extend beyond mere cost reduction, encompassing the tokenization of energy assets, which unlocks unprecedented flexibility, near-instantaneous transactions, and the potential for flourishing secondary markets [161].

4.2.7. Cryptocurrencies, tokens, and startup fundraising

The general structure of the cryptocurrencies, tokens, and startup fundraising use case, shown in Fig. 11, is formed by three layers, namely the token, the governance, and the technology layers. The governance layer includes organizational processes such as network governance, token holder inclusion, DM processes, and off-chain governance systems. The technology layer deals with technical issues such as validation algorithms and protocol code. The token layer is the link between the governance and technology layers.

Different kinds of classification exist for the Token layer. Cryptocurrencies can be categorized as first-generation applications of DLT systems [162]. In fact, the DLT technology was initially invented to

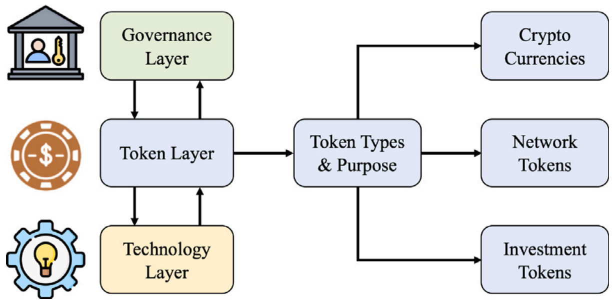

Fig. 11. DLT system layers, token types, and purposes.

create an online (crypto) currency to bypass banks and direct, transparent, and trustworthy transactions. The starting point was the 2008 anonymous paper by Nakamoto [163], who introduced Bitcoin, but also the concept of blockchain in general (note that Nakamoto was building on ideas from earlier work of Leslie Lamport and others). Readers may consult the report of the US National Institutes for Standards and Technology [164] for a full discussion and presentation.

The diagram of Fig. 11 also illustrates the use of network tokens within a specific network or application. For example, in the structure proposed to the PowerLedger P2P trading model in [165], POWR is a cryptocurrency, and Sparkz is a network token. A similar approach was also presented by [166], where authors demonstrated a token-based P2P energy market that is suitable for DR.

In recent years, there has been a high increase in emerging cryptocurrencies, mainly as an Altcoin. Altcoins can be defined as any cryptocurrency other than Bitcoin. General applications of this segment focus on cryptocurrencies to tokenize assets and passively invest in the issuing entity or asset. To tokenize assets such as renewable energy plants, first, the asset is split into small pieces. Tokens are created and issued on the blockchain as digital presentations of each piece. On the network, the tokens can be traded between the participants without any central intermediary. So, it can be as an instrument for funding as ICO or Secure Token Offering (STO), which is growing day by day by increasing awareness of the potential benefits of DLT [167]. Thanks to this, many start-ups pass around the usual fundraising methods of capital investors and instead utilize crowd-funding investment through ICO. In this method, DLT-based currency tokens that will be used in start-ups' network ecosystems are sold. Since 2016, more than USD 31 billion has been raised via ICO [168].

As mentioned in Section 3, consensus mechanisms are an active research field, and there are multiple consensus protocols that are already implemented in various cryptocurrencies such as Bitcoin and Ethereum. However, even though consensus protocols are becoming more secure and computationally efficient [169] (mainly due to environmental and climate change problems [170]), several emerging vulnerabilities are still persisting that can limit the full utilization of cryptocurrencies [171].

One of the main obstacles is the current cryptocurrencies' energy usage. This has led to a focus on replacing the PoW mining process with less power-consuming processes like PoS, as XinFin's XDC protocol [172]. A mitigating example for one of such vulnerabilities was proposed and presented by [173], where authors are demonstrating a new DLT key that is tolerable against Byzantian Faults and prevents collusion between miners and data receivers. The result shows that crypto-wallets, which utilize demonstrated key management, are more secure from cyberattacks while also providing enhanced privacy.

Another research focusing on energy usage was presented in [174]. Acknowledging the high energy demands and environmental impact of blockchain mining, the study proposed a three-story facility powered predominantly by renewable sources and cooled via advanced airflow systems with recycled components. Using 672 Bitmain Antminer S9 rigs, the proposed design achieved Power Usage Effectiveness (PUE) of 1.04 and a Data Center Infrastructure Efficiency (DCIE) of 96.15%, with monthly profits surpassing $3.2 million from Bitcoin and $2.3 million from Ethereum.

4.2.8. P2P, local, and regional energy trading

As more DER, smart meters, and two-way communication facilities enter the power system, consumers can take a more active role in the electricity supply chain. This allows for a reconstruction of the traditional energy markets. In the new paradigm, the markets transit toward a bottom-up structure, with prosumers acting as active market participants. Utilizing DLT can enable this transition by removing the need for a third party in the energy transaction, speeding up the validation process, and improving the privacy issues of the market participants. In fact, the most popular application of DLT in the energy sector is to turn the existing grid into a P2P network so that customers can trade electricity with each other [13]. For example, they can buy and sell rooftop solar energy. However, despite the ambitions of several blockchain start-ups, an utterly decentralized business network, such as the one that surpasses the existing centralized network, is unlikely to be realized soon. Since many of these projects rely on the current grid and all the transactions are virtual, as similarly performed by AGL Energy which was funded by the Australian Renewable Energy Agency (ARENA) [175]. Still, the DLT can enable more participants to trade, even if it does not replace the grid. However, in areas where power grids may be non-existent or problematic, there are opportunities to build P2P networks. For instance, in Bangladesh, ME SOLshare is connecting homes so that they can trade extra energy from rooftop solar panels [176]. Other initiatives are based on the purpose of incentivizing more DER, like the digital platform developed by the German utility WSW Wuppertaler Stadtwerke, facilitating direct trade between local renewable energy producers to consumers [177].

Several pilot projects have developed trading platforms by utilizing DLT and tokens to facilitate direct P2P trading between prosumers and consumers. A commonly used blockchain-based platform is Ethereum due to its capability of applying programmable transactions in the form of smart contracts [178]. Examples include the P2P market implementation in [179]. Hyperledger Fabric is also a popular choice, e.g., founding the base of the blockchain-based market framework constructed in [180].

In the literature, the P2P market structures are classified into three categories [181], as depicted in Fig. 12:

- Fully decentralized markets;
- Community-based markets;
- Hybrid markets.

In a fully decentralized P2P exchange (see Fig. 12a), customers can negotiate with each other directly to agree on the trading parameters without any centralized administration.

In community-based P2P markets (see Fig. 12b) a group of prosumers in a neighborhood can be formed to optimize the use of shared energy resources and provide flexibility services by trading energy with the existing market through energy community aggregators (see, e.g., [182,183] for example models). The study in [184] presents a P2P trading market structure in a local community, which used decentralized exchange for the financial layer and a fast consensus mechanism, where a validator proceeds with the validation of a transaction after polling the opinions of a small random group of validators. The community members share common objectives and interests even though they are not in the same locality.

A hybrid market (see Fig. 12c) is a mixture of community-based and fully decentralized markets in which each community and each customer can interact with each other while keeping their market assets. An example of this setup is demonstrated in [185], where agents within a VPP can negotiate both with each other and with

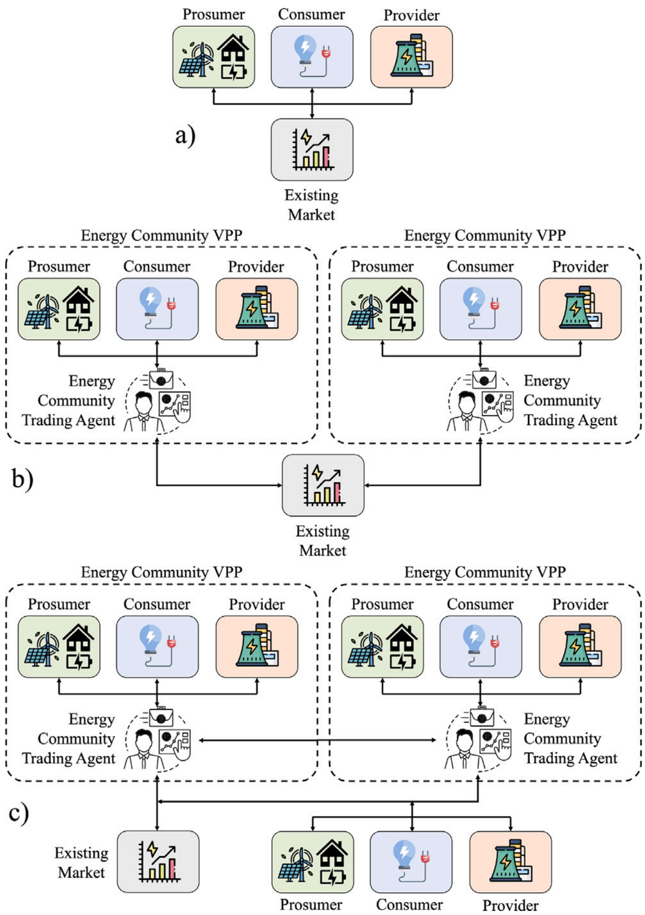

Fig. 12. Decentralized energy trading market designs [181]; (a) Full P2P market design, (b) Community-based market design, (c) Hybrid P2P market design.

other VPPs through a P2P energy trading coordinator. The transactions are performed through smart contracts on a public Ethereum-based platform.

The researcher in [186] proposed a transactive energy management system leveraging blockchain technology and Multiple Agent Modeling (MAM) to enable P2P energy trading and enhance the reliability of energy efficient grids. The system uses a decentralized, agent-based approach, where services, sellers, and customers interact dynamically to trade energy based on real-time data and economic conditions. The framework addresses challenges such as demand-response management, integration of renewable resources, and grid stability, demonstrating improved power utilization and reduced load spikes through modeling and evaluation.

A similar research was also performed by Shang et al. [187] which presented a comprehensive decentralized framework to enhance P2P systems. The study introduces a strategy-varying auction mechanism based on credibility, a three-person non-cooperative transaction model and a novel Proof of Realistic Energy (PoRE) consensus mechanism. Unlike the other assessed studies for this manuscript, this approach addresses key challenges in existing P2P models, including transaction fairness, default rates, and DER unpredictability. According to the presented results, with the proposed methodology, prosumer profits were up by 26.7% meanwhile consumer savings were up by 31.7%.

Meanwhile, the research presented in [188] introduced a robust protocol named PA-Bill to address privacy, accountability, and fairness challenges in P2P energy billing. PA-Bill leverages homomorphic encryption to safeguard user data and blockchain to provide transparency and immutability in billing records whereas a universal cost-splitting

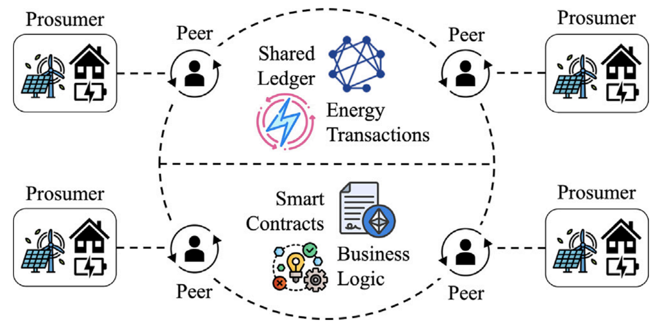

Fig. 13. An example shared ledger energy trading network resulting transaction [190].

mechanism ensures fair treatment of deviations between committed and actual energy usage, while an integrated dispute resolution system reinforces trust and non-repudiation. According the performed research, the protocol is scalable, supporting communities of up to 2000 households, and demonstrates computational efficiency without compromising on privacy or accountability. Hence, mitigating one of the core problems within the P2P energy trading domain.

Similarly, Gurjar et al. [189] presented a comprehensive blockchain-based framework designed to facilitate secure, efficient, and transparent P2P energy trading within microgrids. The proposed framework introduced a novel PoC consensus mechanism to significantly reduce latency (to 3 s), increase throughput (up to 42 transactions per second), and ensure secure transaction validation. Additionally, the system utilized smart contracts to automate trading, prevent double spending, and dynamically adjust energy prices based on supply–demand ratios. It replaces complex double auctions with a streamlined single-price mechanism and supports direct communication among nodes for real-time responsiveness.

Fig. 13 shows an example of a shared ledger-based energy trading network and resulting transaction. A typical DLT-based energy transaction in its simplest form involves two homes that are connected via a platform with the ability for one to sell, e.g., excess solar power to another. This requires two Blockchain transactions: a secure transmission of data about the amount of energy generated and a payment to the seller.

If a transaction is incentivizing a buyer, then a digital currency is used to complete the transaction. Smart contracts and tokens let buyers and sellers deal directly, with secure bidding locked in a tamper-proof DLT ledger. Know Your Customer (KYC) and Anti-Money Laundering (AML) ensure trust and compliance, making DLT the new frontier for transparent, secure energy markets [191]. Although DLT provides the ability to match energy generation and demand between the two consumers automatically, it still requires exploring the role of the utility in P2P energy transactions [192]. Here, a utility in the form of a system operator node is still needed to check if the set of P2P energy transactions agreed still satisfy the physical constraints of the system (such as voltage and current limits of the cables and other system components). The operator, in this case, would have to run the power flow algorithm to check viability and propose changes to the agreed trades otherwise. Two other examples are shown in [193,194]. In [193], an Ethereum-based P2P energy trading is presented, which preserves the privacy of user identities and energy transactions. In [194], blockchain is used to record historic transactions to inform optimal pricing strategies for DER participating in energy trading.

Energy transactions in the local energy trading are bidirectional and are considered as the final step of the P2P energy trading. The process of actual energy transactions starts with the submission and matching of bids through which a trade is made. Once the trade cycle is complete, a Distribution System Operator (DSO) may evaluate the orders and accept or reject them. The actual energy exchange or transactions take place after these two steps as shown in Fig. 14.

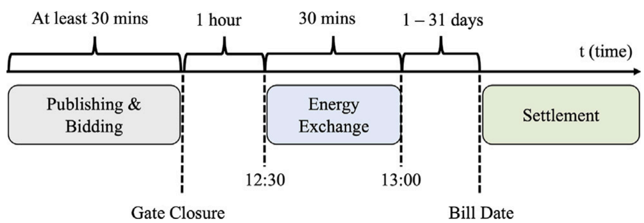

Fig. 14. A typical example of processing of an order for a transaction [195].

However, the P2P energy transactions will result in large power flows in multiple directions at the distribution level [196]. Such transactions might disturb the network up to an extent where they may violate the physical limits of the lines in the network and may compromise its operation, causing over-voltage, capacity, and congestion issues, and higher losses [197]. In this regard, DLT technology keeps track of all the information regarding a transaction. If certain energy transactions lead to a violation of a network constraint, a market structure [198] based on DLT Blockchain technology rejects those transactions. This will help maintain resilience and security of supply if that transaction poses a threat. A noteworthy observation is such DLT-based P2P network may involve multiple smart contracts. A recent study by researchers from the PNNL demonstrated a smart contract framework for the transactive energy market that would be relevant in forming a practical DLT-based P2P solution [199].

4.2.9. Grid management and flexibility/grid services

The concept of local or P2P energy networks enabling trade within the neighborhood has existed for quite some time, and several initiatives have been developed in many countries. Governments, private organizations, and firms are now investing in funds to boost the adoption of such markets. These markets have the potential to transform centralized networks into decentralized ones, where the power can flow in multiple directions due to local energy transactions. This requires better coordination between Medium Voltage (MV) and Low Voltage (LV) networks, transparent and accurate system data, visibility of distributed resources, and automated grid operations [13].

However, with the participation of several thousands of consumers in such markets, the computational requirements increase manifolds. Moreover, consumers sharing their confidential personal data are always under threat of data breach or attack [114]. Finally, the traditional trading mechanism is always supervised by an intermediary entity, i.e., DSO, which restricts flexibility, abandoning the very concept of autonomous trading. Therefore, all these limitations render the concept of a potential local trading framework unfeasible with the current market structure [200]. Hence, integration of such markets in the present power grid would need the proper platform to effectively manage networks and assets.

Decentralized networks could be managed by the evolving DLT, which can provide flexibility services or asset management [54]. In other words, DLT can register every transaction and store time-stamped information which can be used in several ways to achieve optimal grid management without the need for expensive network upgrades [201]. It would help to trace the power flow associated with each transaction which would be very crucial in computing node injections. Thus, obviating the need for a central control entity by keeping track of distributed energy transactions [202]. DLTs are also applicable to annotate energy losses associated with each transaction. Allocation of the losses will eliminate the transactions from distant sources and incentivize participants to maintain the lines to operate well below their thermal limits [203]. Distribution grids may face congestion issues due to DER peak generation, thereby causing over-voltage and power flow issues on lines and transformers. A study in [204] concludes that no similar approach to DLT technology has been presented yet for stable congestion management.

Alternative scenarios of grid management, i.e., DR and resource aggregation that were not present in the traditional market, are only possible due to the development of smart contracts with the DLT. Prosumer premises equipped with IoT metering devices develop smart contracts, enabling excellent load control strategies [205] to manage energy demand flexibility. On the other hand, for flexibility aggregation, smart contracts define the prosumers' baseline profile and expected adjustments in terms of the amount of energy flexibility to be shifted [206]. The energy transactions are stored in blocks replicated while the smart contract will self-enforce each time the state of the distributed ledger is changed. The study in [207] proposes a blockchain framework for trading of ancillary services and reactive power between independent market participants, such as Distributed Generation (DG) units and the system operator. The framework is based on a two-layer blockchain topology that improves scalability and time for processing transactions.

An emerging scenario of effective grid management with Community-oriented VPP is also attracting researchers and utility operators worldwide. It is built on top of the P2P local energy trading and decentralized flexibility management [181]. It finds its application where there is a need to optimize the output from multiple local generation assets (i.e., wind turbines, small hydro, photovoltaic, DG, etc.) meant to supply local communities or feed excess power to a distribution network. Sunverge Energy utilizes this multi-objective optimization approach in their platform for VPP to facilitate grid-aware, near real-time control of DER [208].

Transparency, traceability, and operational coordination in renewable energy supply chains are integral to grid management and flexibility, as they focus on performance optimization, risk assessment, and system integration within energy infrastructure. Therefore, the research performed by Babaei et al. [209] presented an integrated decision making methodology for evaluating blockchain adoption in renewable energy supply chains. By combining MCDM techniques with optimization tools such as Benefit of Doubt (BoD), Data Envelopment Analysis (DEA), and Free Disposable Hull (FDH), the authors identify and prioritize challenges such as high investment costs, system design complexity, and inadequate technological development. Through a case study on Iran's renewable electricity sector, it demonstrated the robustness of its framework in guiding supply chain managers toward more efficient, resilient blockchain adoption strategies.

DLT-based smart contracts may also provide management in a distributed fashion [210] by creating optimal coalitions of prosumers. This will enable the integration of assets-specific constraints and the community-level objectives as well as global objective functions associated with the service to be provided.

As an example, in [211], Energy21 [212] and Quantoz presented the first ideas about applying blockchain in a new market model. They aim to provide a flexible market for demand-side services. Blockchain is the technology that allows a large number of transactions in the local market and adopts the role of DSO. They propose the Layered Energy Systems (LESs). Other companies and startups have come up with the initiative of implementing DLT technology aimed at providing grid management solutions. They offer management of DERs (Alectra [140]), decentralized trading (NRG Coin [213]), aggregation of demand resources (Omega Grid [214]), congestion management (Gridchain), load balancing (PROSUME [215]), DR (EvolvePower), community-based energy management services (CEDISON), and flexible storage capacity (TenneT [216], Sonnen [217]). Equigy is a blockchain-based balancing platform developed by European TSO to track and validate grid services from aggregated, small-scale flexibility resources [218].

4.3. Governance, regulation, and enablers

4.3.1. Regulation

Energy systems are gradually becoming more decentralized and complex, with larger numbers of active market participants and a greater range of energy services. Regulators are, therefore, increasingly requiring energy companies to provide huge amounts of detailed information in order to ensure regulatory compliance and audit processes are becoming increasingly onerous [219]. As the requirements for data provision for regulators increase, the security risks of sensitive company data also increase.

The use of a suitable energy DLT platform for regulatory compliance purposes, as that depicted in Fig. 15, would provide the required transparency for regulatory compliance and enable secure access to clean, tamper-proof company data, with well-defined data access permissions [13].

Some national regulatory entities now employ open energy data platforms in order to certify the quality and accuracy of national energy sector data, which is expected to provide security benefits by ensuring that data stored on the platform cannot be modified without the consent of the parties involved [220].

In energy efficiency applications, energy regulatory bodies issue White Certificates (WCs), also called energy savings certificates or energy efficiency credits, in order to validate that a certain reduction in energy consumption relative to a pre-defined baseline has been achieved. WC can be obtained either through the implementation of approved energy savings projects or by purchasing wWCs from third parties via a spot market [221]. The spot market for WC needs to be overseen by an independent regulator in order to verify and approve transactions. DLT-based smart contracts have the potential to greatly simplify WC processes, eliminating much of the regulatory oversight burden.

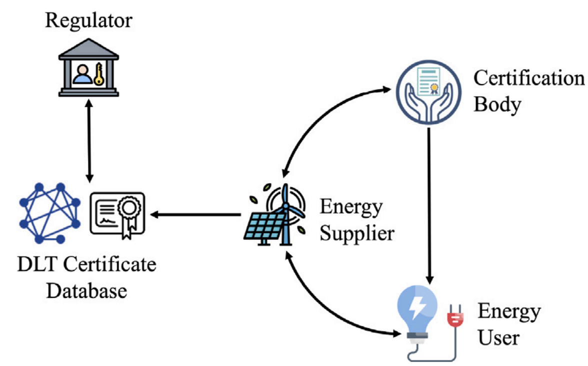

Fig. 15. Example of a DLT platform for regulatory compliance purposes.

4.3.2. General purpose initiatives & consortia

As a new technology with the potential to be adopted in various applications, innovations around blockchain opened a large field of new opportunities. Several initiatives and consortia were settled to promote knowledge, cooperation, and innovation around decentralized technologies as a reaction.

By definition, a consortium is created by a group of two or more organizations (public or private) with the objective of joining forces in a shared activity, in this case, blockchain technologies. Some of these consortiums or initiatives are multi-sectoral; thus, they provide services for multiple sectors, while others are energy-centered. A consortium may be international, embracing companies worldwide or for specific regions, or typical for a particular nation. Additionally, some initiatives are technically oriented, while others are more general. The latter can incorporate a broader range of dimensions in their agenda, such as business, social, and regulatory or political. Alastria is an example start-up for such multi-sectoral initiative. It is a consortium of Spanish companies that brings together digital ideas and support for legal advice. Its purpose is to promote the digitalization of companies and entrepreneurs and the interactions to learn new business models. Energy companies that are part of the consortium are Repsol, Cepsa, Aduriz energia, Battergy, EDP España, Endesa, Iberdrola, MibGas, Naturgy, Omie, Red Electrica de Espana, Siemens Energy, The South Oracle and Elecnor [222].

4.3.3. Multi-national conglomerate

Multinational enterprises encompass the majority of the economic activity in the world nowadays. They were initially conceived as joint-stock companies, later developing into capital and limited liability structures. With the appearance of Bitcoin, the significant technological advance of DLT meant a paradigm shift for multinational conglomerates [223].

As seen in [224] DLT developments are expected to improve governance efficiency when compared to traditional markets, networks, firms, contracts, and even governments. As new initiatives experience and develop DLT technologies (e.g., smart contracts and incentive mechanisms) to organize cross-border human activity without relying on centralized hierarchical schemes, the need for multinational conglomerates has been questioned by some researchers [225].

Nonetheless, the implementation of DLT also has important positive implications, in particular for multinational conglomerates: it allows them to limit the liability associated with new markets [226], amplify trust building [227], accelerate internationalization [228], and enhance knowledge creation and improves knowledge transfer and learning [229]. By doing all this, DLT applications can potentially reduce the risk and uncertainty perceptions which can drive international accord, particularly for the energy sector DLT presents important potential for international exchange of electricity, as well as the transfer of ownership of physical energy assets with smart contracts for multinational conglomerates.

As discussed in previous sections, DLT initiatives promise to provide numerous services (e.g., computation, storage, applications), but more than the services themselves, these initiatives offer a very novel organizing model for the provision of these services with global scale capabilities [230]. Aware of this, multinational enterprises are taking on DLT at an increasing pace: by early 2020, a total of 35 multinational conglomerates had applied for 212 blockchain-related patents in China [231]. Large conglomerates like Wipro are able to offer technical consultancy for blockchain deployment over a wide range of applications within the energy sector, such as P2P trading, digital identity, and payment solutions [232].

4.3.4. National conglomerate

A number of initiatives are being led by national governments for the development of DLT: As an alliance between the government of China, national banks and technology companies, BSN unites efforts in the development of DLT and hopes to share results between its members. BSN's collaboration scheme on a national level expects to reduce costs of blockchain business initiatives by 80%, according to their white paper [233]. Australia is leading the path to the global standardization of support for blockchain through the ISO [234] and the development of its Roadmap for Blockchain Standards [235], identifying priority areas for standardization in the blockchain. Among other examples of these national-led initiatives are the case of India and Bangladesh, which produced their own strategy for the development of DLT technologies in [236,237] respectively. Supranational entities are also developing their own agreements for the regulation, promotion, and development at the national level; the European Union launched its own initiative of this kind through the European Blockchain Partnership: the International Association of Trusted Blockchain Applications (INATBA) [238].

Nationwide DLT applications particular to the energy sector are still under development. Nonetheless, seeing the example of China's General Administration of Customs—that monitors 26 international borders using blockchain [233], it is envisioned that the potential for information sharing and smart contracts that DLT offers for national electricity entities will be exploited in the near future.

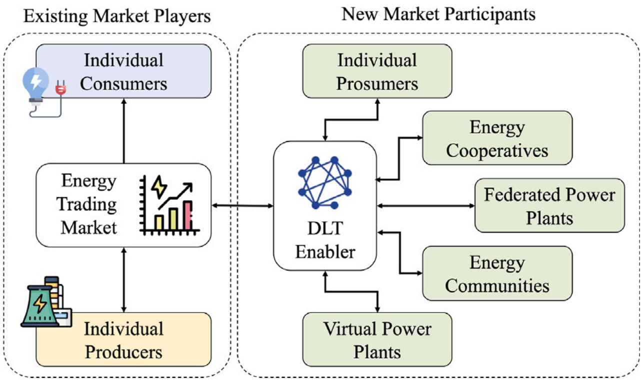

Fig. 16. DLT enabler for new market participants.

4.3.5. National labs and other national research institutes

Organizations within this field face the unique challenge of advancing research in a manner that fulfills the goals of their sponsoring organizations and, especially, the needs of their nation. This may include supporting their economy, advancing their infrastructure, and addressing their social equality and inclusion goals.

As such, multiple research avenues are being currently explored, which range from finding and evaluation of blockchain as a support system [239–243], to securing grid communications [244], enabling grid transaction [245], enabling distributed computation of grid states [246–248], securing carbon credits [249].

4.3.6. Non-partisan/non-profit associations

Non-partisan/non-profit organizations face challenges of assuring accountability and transparency and managing overheads [250]. While DLT initiatives have their limitations, they also offer improvements in terms of anonymity, trust, and security for their users while also eliminating the need for intermediaries, and as such, they can change the way non-profits operate.

A number of initiatives for non-profits can be found in [251–254] and these can be extrapolated to future applications in the energy sector (e.g., crowdfunding for the installation of new energy infrastructure in places that currently have no access to electricity, energy donations through smart contracts, access to the market of green certificates, etc.).

4.3.7. Enabling new market participants

As DER and flexibility resources become part of the network, energy usage evolves, and grids transition from passive to active networks. As a consequence, new schemes of participation are emerging. Traditional small consumers are evolving into small-scale producers and prosumers; grids are evolving into smart grids, microgrids, and energy communities [56]. With these, new markets and participants are becoming relevant as well. These new participants come with challenges (e.g., issues associated with transparency and trust for their transactions and record-keeping). Therefore, DLT is expected to play an important role in their development, by enabling the adoption of decentralized trading platforms, such as that schematically represented in Fig. 16.

Initiatives like the CENTS project [255], where individuals and communities can trade electricity on a cooperative model using a blockchain-based platform, are disrupting the electricity sector, not only diversifying the type of participants on the market but including SE concepts that were not applied before to the sector. In a similar way, Federated Power Plant (FPP) and VPP aggregate resources of several users to facilitate trade in the electricity market [256–258]. A good example of this is community-based VPP [258], a project proposing a new model for the pooling of generation and flexibility resources, increasing the level of participation and control of individual participants.

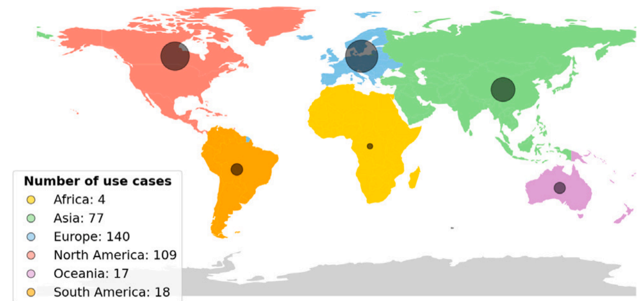

Fig. 17. The geographical distribution of investigated energy-blockchain businesses.

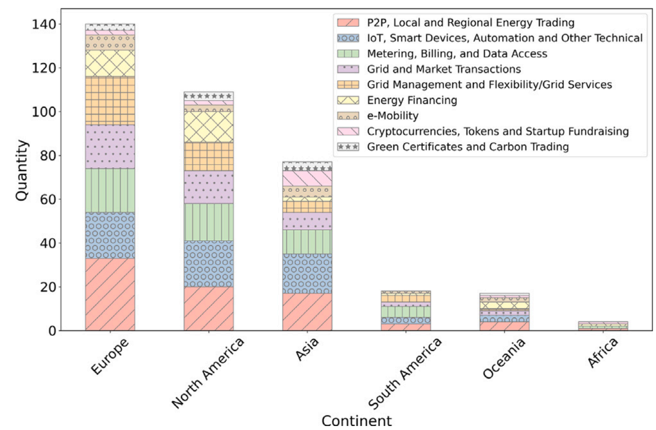

Fig. 18. The distribution of use cases for the investigated companies.

4.3.8. Energy consultant

Expert advice in a particular area has long been a common practice in business, engineering, and science. Therefore, consultancy firms are also adopting blockchain and distributed ledger technologies as part of their services.

There is a wide variety of consultancy firms providing blockchain expertise. Some of these are small consultancy firms specializing in blockchain technical details or their application for a given sector like energy. In contrast, larger consultancy firms also held blockchain services in their portfolios. For example, Ponton is a well-known initiator of some projects but also provides a consultancy service as a blockchain expert. They have their Blockchain Framework that is applied in their projects. EnerChain is one of the projects of which Ponton has been a part. They developed the EnerChain 1.0, which they claim to be ready to start performing P2P transactions. Other projects are New 4.0 (manage grid congestions), ETIBLOGG (allow small producers to participate), GridChain (TSO/DSO coordination), and Enerchain. They developed the WRMHL as a blockchain framework to offer services to different businesses.

4.4. Evaluation of literature and market surveys

The investigated companies are categorized into two main clusters: start-up and utility projects. Over 100 well-known pilot projects and start-ups have been analyzed. Fig. 17 shows the geographical distribution diagram, and Figs. 18 and 19 present the use cases and distributions of the organization types of the surveyed companies. The following are some of the key insights:

- With 84 active companies/projects, the epicenter of energy-blockchain is in Europe, followed by North America with 52 active companies and Asia with 42;
- The top three countries are the USA with 47, Germany with 19, and the UK with 11 projects;

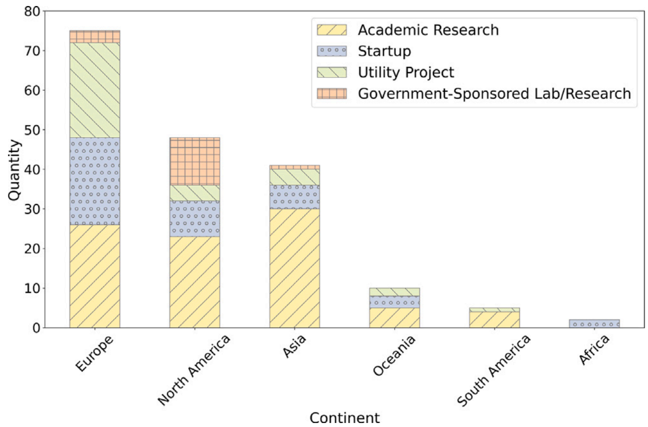

Fig. 19. The distribution of DLT initiatives for the investigated companies.

- In terms of use cases, the most popular one is “P2P energy trading” with 75 applications. “IoT, smart devices, automation, and other technical” is in the second position with 61 applications, amounting to 24.4% of the companies. The third most popular use case is “Metering, billing and data access” with 50 applications.
- The top three countries for the most use cases are the USA with 97 companies, Germany with 33, and the Netherlands with 19;
- Germany leads Europe in “P2P energy trading”, with 33 use cases, and in “grid management and flexibility services”, with 22 use cases. The UK, with 21 use cases, is the leader in “IoT, smart devices, automation, and other technical innovations.” In North America, the USA dominates in “IoT, smart devices, and automation” (21 use cases), “P2P energy trading” (20 use cases), and “metering, billing, and data access” (17 use cases). In Asia, India leads in “IoT, smart devices, and automation” (18 use cases), “P2P energy trading” (17 use cases), and “metering, billing, and data access” (11 use cases).
- The USA emerges as a significant hub for “Academic Research” with 19 active companies showcasing its leadership, followed by India and the UK with seven and six projects, respectively. Europe stands out in “Utility Projects”, with Germany and the Netherlands each hosting six active companies and Switzerland closely behind with four, highlighting a strong European engagement. Meanwhile, the “Start-up” landscape is led by the USA with nine innovative companies, Germany with six, and Australia, indicating a vibrant and diverse interest across continents in leveraging blockchain technology within the energy domain. However, by October 2024, only two-thirds of the start-up companies screened since the start of this work appear active, and some of them have shown no recent activity or public updates, such as [259], as illustrated in Fig. 20. Detailed information can be found in Table B.11.
- About only 2.6% of the businesses are new participants with novel ideas, which shows that DLT technology can pave the way for expanding the energy industry in different directions.

5. Decision making method

This section outlines a DM framework for assessing the use of blockchain technology in energy systems. The process is based on seven key criteria: (1) technological maturity, (2) interoperability, (3) scalability and transaction speed, (4) cybersecurity, (5) value creation and economic viability considering Operational Expenditures (OPEX) and Capital Expenditures (CAPEX), (6) energy consumption and contribution to the United Nations Sustainable Development Goals (UNSDG), and (7) legal and legislative factors. These criteria provide a structured approach for evaluating the feasibility, benefits, and challenges of blockchain in energy applications.

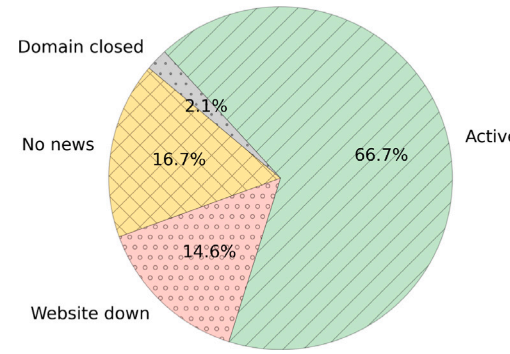

Fig. 20. Status of start-up companies with DLT initiatives per October 2024.

A rigorous and context-aware evaluation of blockchain use cases in the energy sector requires a systematic approach to identifying relevant decision-making (DM) criteria. In this study, a two-stage process was adopted, combining insights from academic and industrial literature with practical expertise from a diverse panel of domain professionals. The expert panel comprised 20 individuals representing a broad cross-section of the energy and digital technology landscape: 8 from academia with expertise in energy systems, computer science, and digital innovation; 7 from industry, including representatives of energy utilities, blockchain startups, and smart grid solution providers; and 5 from governmental and standardization bodies such as IEEE and national energy regulators. Each expert had a minimum of five years of professional experience, with several actively contributing to international blockchain-energy pilot projects and standardization efforts. This diverse and multidisciplinary composition enabled the selection of DM criteria that are both theoretically grounded and practically relevant, supporting a robust evaluation and prioritization of real-world energy blockchain use cases.

5.1. Decision making criteria

- **C_1-Technological Maturity:** Assessing the maturity of a particular technology involves determining its readiness for operations across a spectrum of environments with a final objective of transitioning it to the user. Analyzing the maturity of a specific blockchain technology is required for wider adoption of DLT-based system for a critical infrastructure like the electric grid.
- **C_2-Interoperability** For emerging smart grid applications, various cyber–physical components like IoT devices, communication capability, and advanced metering infrastructure are expected to interact with each other within a multi-dimensional and multi-layer ecosystem. Therefore, interoperability is a key criterion for energy blockchain applications that can satisfy the safe and robust operation of the proposed system and subsystems.
- **C_3-Scalability and Transaction Speed:** A transactive energy system is required to handle interactions among a number of stakeholders of the energy market or systems landscape like power generators, utilities, power traders, prosumers and in some business models, aggregators. In some cases, intelligent devices and systems may also appear on the scene as agents with autonomous interactions. Therefore, for an energy blockchain network, an essential evaluation criterion is to ensure that a vast number of customers and systems can participate in the blockchain-enabled energy market at the same time. Transaction speed for the energy blockchain use case refers to how fast the power market and systems-related operations and transactions can be performed with respect to transaction volume. The transaction speed can

have a vast effect on bid-based sub-hourly markets such as a 15-minute market or a 5-minute market. Therefore, an important evaluation criterion for any energy blockchain solution is the maximum allowed volume of transactions per second without overloading the network.

- **C_4-Cybersecurity:** Cybersecurity aspects investigate risks associated with the cross-cutting fields between Cybersecurity, Blockchain DLT, and energy use cases. With multiple stakeholders accessing the same communication and trading network, the Cybersecurity aspect of the underlying blockchain network should be analyzed to ensure the protection of the critical infrastructure. Furthermore, evaluation of the Smart Contracts in terms of Cybersecurity and attack surface aspects of Blockchain DLT use cases in the field of Energy are other perspectives to be improved. This is particularly important for off-the-chain data inputs to the blockchain (Oracles), as blockchain consensus mechanisms are generally oblivious to ant tampering before the data gets to the Blockchain.
- **C_5-Value Creation and Economic Viability (OPEX and CAPEX):** Applying blockchain for energy systems requires financial investment, which requires analyzing the economic viability of such a digitalization investment project. CAPEX of such investments may include project management, system design, and development of both the hardware and the software components. Meanwhile, the OPEX includes the cost components regarding the operation and maintenance of the established system and can also include the associated transaction fees. One major advantage of using blockchain for energy infrastructure is the fact that it can streamline settlement processes. This is particularly relevant for P2P transactions as blockchain can eliminate third parties. Hence, it is essential to assess the economic values created by blockchain and how it can accelerate the processes, increase efficiencies by reducing costs, and/or increase the benefits.
  One major advantage of using blockchain for energy infrastructure is allowing P2P transactions, which can eliminate third parties. Hence, it is essential to assess the economic values created by blockchain and how it can accelerate processes, increase efficiencies by reducing costs, and/or increase benefits.
- **C_6-Energy Consumption and Contribution to United Nations Sustainability Goals (UN SDG):** In general, making any PoW consensus mechanism-based cryptocurrency is anti-efficient from an energy consumption perspective, which is true for permissionless DLT architecture. However, a permissioned DLT framework (e.g., Hyperledger Fabric) relies on less energy-intensive consensus protocols. Therefore, it is crucial to evaluate the use cases with respect to their corresponding effect on overall energy consumption. The application of blockchain to the energy ecosystem should be evaluated with respect to some of the goals of the 17 UN SDGs. For example, applying blockchain can pave the way to creating technologies for industry practice (goal number 9), making affordable and clean energy (goal number 7) possible, and creating the opportunity to develop sustainable cities and communities (goal number 11).
- **C_7-Legal and Legislative:** Blockchain in energy systems requires the application of smart contracts to govern the rules of the energy market. However, these digital rules should comply with legal documents and laws are used to declare the specific sets of the rules and the penalty of associated violations. Being a critical infrastructure, the adoption of blockchain in energy applications will require the support of policymakers and public acceptance, as these can potentially influence investment decisions.
  As a critical infrastructure, the adoption of blockchain in energy applications will require the support of policymakers and public acceptance, as these can potentially influence investment decisions.

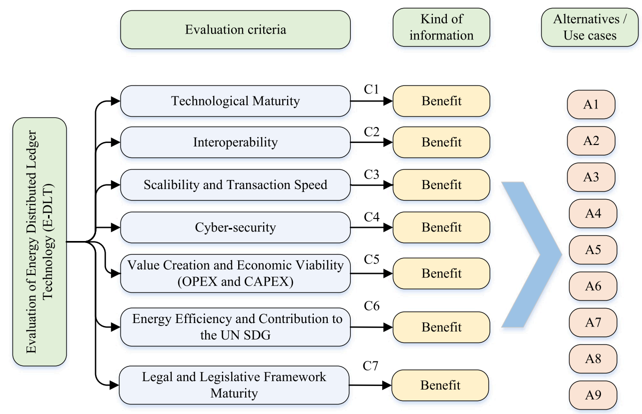

Fig. 21. The hierarchy of the E-DLT DM problem.

5.2. Literature review on q-ROF sets

In this study, q-ROFs based DM model is applied. The concept of q-ROFs is introduced in [29] to address the uncertain and imprecise information.

A variety of q-ROFs-based multi-criteria DM methods have been integrated into DM problems. Zolfani et al. [260] proposed a new model including q-ROFs based VIKOR method for prioritizing new strategies for regionalization of the global supply chains. Alkan and Kahraman [261] presented a q-ROFs based TOPSIS for the evaluation of government strategies against the COVID-19 pandemic. Xiao et al. [262] improved an integrated Best-Worst-Method (BWM) and WASPAS model under q-ROFs to select product manufacturers. Rani and Mishra [263] study a new assessment model based on q-ROFs for the fuel technology selection problem. Darko and Liang [264] proposed some q-ROF Hamacher aggregation operators and their application with the EDAS method for mobile payment platform selection problems. Krishankumar et al. [265] solved the green supplier selection problem using the q-ROF-based VIKOR method. Riaz et al. [266] used q-ROFs and m-polar fuzzy sets under a DM model for a robotic agri-farming problem. Ma et al. [267] applied q-ROFs to capture more risk evaluation information for failure mode and effect analysis. Alsalem et al. [268] presented a novel hybrid model for evaluating and benchmarking trustworthy AI applications in healthcare by using multi-criteria DM techniques under q-ROFs.

5.3. Definition of the proposed DM method

5.3.1. Preliminaries on q-ROF sets

Definition 1. A q-ROF $\breve{\zeta}$ in a finite universe discourse $\tau = \tau_1, \tau_2, \ldots, \tau_n$ is expressed by Yager [29]:

$$\breve{\zeta} = \left\{ \left\langle \tau, \partial_{\breve{\zeta}}(\tau), \wp_{\breve{\zeta}}(\tau) \right\rangle \middle| \tau \in \tau \right\}, \tag{1}$$

where $\partial_{\breve{\zeta}}, \wp_{\breve{\zeta}} : \tau \to [0,1]$ denote the degree of membership and non-membership of the element $\tau \in \tau$ to the set $\breve{\zeta}$, respectively, with the condition that $0 \le \partial_{\breve{\zeta}}(\tau)^q + \wp_{\breve{\zeta}}(\tau)^q \le 1$, where $q \ge 1$.

The degree of hesitancy is described by:

$$\tau_{\breve{\zeta}}(\tau) = \sqrt[q]{1 - \partial_{\breve{\zeta}}(\tau)^q - \wp_{\breve{\zeta}}(\tau)^q} \tag{2}$$

For convenience, we call a $\left\langle \partial_{\breve{\zeta}}(\tau), \wp_{\breve{\zeta}}(\tau) \right\rangle$
q-ROF number (q-ROFN) and characterized by $\breve{\zeta} = \left\langle \partial_{\breve{\zeta}}, \wp_{\breve{\zeta}} \right\rangle$.

Definition 2. Let$\breve{\zeta} = \left(\partial_{\breve{\zeta}}, \wp_{\breve{\zeta}}\right)$, $\breve{\zeta}_1 = \left(\partial_{\breve{\zeta}_1}, \wp_{\breve{\zeta}_1}\right)$, and $\breve{\zeta}_2 = \left(\partial_{\breve{\zeta}_2}, \wp_{\breve{\zeta}_2}\right)$ be three q-ROFNs. Then their operations can be described by Liu and

Wang [269]:

$$\breve{\zeta}^{p} = \left(\partial_{\breve{\zeta}}, \wp_{\breve{\zeta}}\right) \tag{3}$$

$$\breve{\zeta}_1 \cap \breve{\zeta}_2 = \left\langle min\left\{\partial_{\breve{\zeta}_1}, \partial_{\breve{\zeta}_2}\right\}, max\left\{\wp_{\breve{\zeta}_2}, \wp_{\breve{\zeta}_2}\right\}\right\rangle \tag{4}$$

$$\breve{\zeta}_1 \cup \breve{\zeta}_2 = \left\langle max\left\{\partial_{\breve{\zeta}_1}, \partial_{\breve{\zeta}_1}\right\}, min\left\{\wp_{\breve{\zeta}_2}, \wp_{\breve{\zeta}_2}\right\}\right\rangle \tag{5}$$

$$\breve{\zeta}_1 \oplus \breve{\zeta}_2 = \left\langle \sqrt[q]{\partial^q_{\breve{\zeta}_1} + \partial^q_{\breve{\zeta}_2} - \partial^q_{\breve{\zeta}_1}\partial^q_{\breve{\zeta}_2}}, \wp_{\breve{\zeta}_1}\wp_{\breve{\zeta}_2}\right\rangle \tag{6}$$

$$\breve{\zeta}_1 \otimes \breve{\zeta}_2 = \left\langle \partial_{\breve{\zeta}_1}\partial_{\breve{\zeta}_2}, \sqrt[q]{\wp^q_{\breve{\zeta}_1} + \wp^q_{\breve{\zeta}_2} - \wp^q_{\breve{\zeta}_1}\wp^q_{\breve{\zeta}_2}}\right\rangle \tag{7}$$

$$\varpi\breve{\zeta} = \left\langle\left(\sqrt[q]{1-(1-\partial^q_{\breve{\zeta}})^{\varpi}}, \wp^{\varpi}_{\breve{\zeta}}\right)\right\rangle \tag{8}$$

$$\breve{\zeta}^{\varpi} = \left\langle\left(\partial^{\varpi}_{\breve{\zeta}}, \sqrt[q]{1-(1-\wp^q_{\breve{\zeta}})^{\varpi}}\right)\right\rangle \tag{9}$$

where $\varpi > 0$, and p is the complementary set of $\breve{\zeta}$.

Definition 3. A Let $\breve{\zeta} = \left(\partial_{\breve{\zeta}}, \wp_{\breve{\zeta}}\right)$ be a q-ROFN, the score function $S(\breve{\zeta})$ of $\breve{\zeta}$ can be defined by Wei et al. [270]:

$$S(\breve{\zeta}) = \frac{1}{2}\left(1 + \partial^q_{\breve{\zeta}} - \wp^q_{\breve{\zeta}}\right) \tag{10}$$

The score function is described differently by Peng and Dai [271]:

$$S_{\varpi}(\breve{\zeta}) = \frac{1}{3}\left(\partial^q_{\breve{\zeta}} - 2\wp^q_{\breve{\zeta}} - 1\right) + \frac{\varpi}{3}\left(\partial^q_{\breve{\zeta}} + \wp^q_{\breve{\zeta}} + 2\right) \tag{11}$$

Definition 4. A Let $\breve{\zeta} = \left(\partial_{\breve{\zeta}}, \wp_{\breve{\zeta}}\right)$ be a q-ROFN, the accuracy function $A(\breve{\zeta})$ of $\breve{\zeta}$ can be described by Liu and Wang [269]:

$$A(\breve{\zeta}) = \partial^q_{\breve{\zeta}} + \wp^q_{\breve{\zeta}} \tag{12}$$

Definition 5. Let $\breve{\zeta}_i = \left(\partial_{\breve{\zeta}_i}, \wp_{\breve{\zeta}_i}\right)(i = 1, 2, \dots, n)$ be set of q-ROFNs and $\omega = (w_1, \omega_2, \dots, \omega_n)^T$ be weight vector of $\breve{\zeta}_i$ with $\sum_{i=1}^{n} w_i = 1$ and $\omega_i \in [0,1]$. q-rung orthopair fuzzy weighted average (q-ROFWA) and q-rung orthopair fuzzy weighted geometric (q-ROFWG) operators are defined by Liu and Wang [269], respectively;

$$q - ROFWA(\breve{\zeta}_1, \breve{\zeta}_2, \dots, \breve{\zeta}_n) = \left(\left(1 - \prod_{i=1}^{n}\left(1 - \partial^q_{\breve{\zeta}_i}\right)^{\omega_i}\right)^{\frac{1}{q}}, \prod_{i=1}^{n}\wp^{\omega_i}_{\breve{\zeta}_i}\right) \tag{13}$$

$$q - ROFWG(\breve{\zeta}_1, \breve{\zeta}_2, \dots, \breve{\zeta}_n) = \left(\prod_{i=1}^{n}\partial^{\omega_i}_{\breve{\zeta}_i}, \left(1 - \prod_{i=1}^{n}\left(1 - \wp^q_{\breve{\zeta}_i}\right)^{\omega_i}\right)^{\frac{1}{q}}\right) \tag{14}$$

5.4. q-ROFWA operator

Definition 6. Let $\breve{\zeta}_i = \left(\partial_{\breve{\zeta}_i}, \wp_{\breve{\zeta}_i}\right)(i = 1, 2, \dots, n)$ be set of q-ROFNs and $\omega = (\omega_1, \omega_2, \dots, \omega_n)^T$ be weight vector of $\breve{\zeta}_i$ with $\sum_{i=1}^{n} \omega_i = 1$ and $\omega_i \in [0,1]$. The weighted q-rung orthopair fuzzy Hamacher average (Wq-ROFHA) operator can be described by Darko and Liang [264]:

$$\begin{gathered} Wq - ROFHA(\breve{\zeta}_1, \breve{\zeta}_2, \dots, \breve{\zeta}_n) = \\ \omega_1(\breve{\zeta}_1) \oplus \omega_2(\breve{\zeta}_2) \oplus \cdots \oplus \omega_n(\breve{\zeta}_n) = \bigoplus_{i=1}^{n}\omega_i(\breve{\zeta}_i) \end{gathered} \tag{15}$$

$$\begin{gathered} Wq - ROFHA(\breve{\zeta}_1, \breve{\zeta}_2, \dots, \breve{\zeta}_n) = \\ \left(\sqrt[q]{\frac{\prod_{i=1}^{n}\left(1+(\sigma-1)(\partial_{\breve{\zeta}_i})^q\right)^{\omega_i} - \prod_{i=1}^{n}\left(1-(\partial_{\breve{\zeta}_i})^q\right)^{\omega_i}}{\prod_{i=1}^{n}\left(1+(\sigma-1)(\partial_{\breve{\zeta}_i})^q\right)^{\omega_i} + (\sigma-1)\prod_{i=1}^{n}\left(1-(\partial_{\breve{\zeta}_i})^q\right)^{\omega_i}}},\right. \\ \left.\frac{\sqrt[q]{\sigma}\prod_{i=1}^{n}(\wp_{\breve{\zeta}_i})^{\omega_i}}{\sqrt[q]{\prod_{i=1}^{n}\left(1+(\sigma-1)(1-(\wp_{\breve{\zeta}_i})^q)\right)^{\omega_i} + (\sigma-1)\prod_{i=1}^{n}\left(\wp_{\breve{\zeta}_i}\right)^{q\omega_i}}}\right) \end{gathered} \tag{16}$$

where $\sigma > 0$ and $q \geq 0$.

When $\sigma = 2$, the q-ROFHA operator transforms into the q-rung orthopair fuzzy Einstein average (q-ROFEA) operator.

5.5. q-ROFWG mean operator

Definition 7. Let $\breve{\zeta}_i = \left(\partial_{\breve{\zeta}_i}, \wp_{\breve{\zeta}_i}\right)(i = 1, 2, \dots, n)$ be set of q-ROFNs and $\omega = (\omega_1, \omega_2, \dots, \omega_n)^T$ be weight vector of $\breve{\zeta}_i$ with $\sum_{i=1}^{n} \omega_i = 1$ and $\omega_i \in [0,1]$. The weighted q-rung orthopair fuzzy Hamacher geometric mean (Wq-ROFHGM) operator is defined by Darko and Liang [264]:

$$\begin{gathered} Wq - ROFHGM(\breve{\zeta}_1, \breve{\zeta}_2, \dots, \breve{\zeta}_n) = \\ \left(\frac{\sqrt[q]{\sigma}\prod_{i=1}^{n}(\partial_{\breve{\zeta}_i})^{\omega_i}}{\prod_{i=1}^{n}\left(1+(\sigma-1)(1-(\partial_{\breve{\zeta}_i})^q)\right)^{\omega_i} + (\sigma-1)\prod_{i=1}^{n}\left(\partial_{\breve{\zeta}_i}\right)^{q\omega_i}},\right. \\ \left.\sqrt[q]{\frac{\prod_{i=1}^{n}\left(1+(\sigma-1)(\wp_{\breve{\zeta}_i})^q\right)^{\omega_i} - \prod_{i=1}^{n}\left(1-(\wp_{\breve{\zeta}_i})^q\right)^{\omega_i}}{\prod_{i=1}^{n}\left(1+(\sigma-1)(\wp_{\breve{\zeta}_i})^q\right)^{\omega_i} + (\sigma-1)\prod_{i=1}^{n}\left(1-(\wp_{\breve{\zeta}_i})^q\right)^{\omega_i}}}\right) \end{gathered} \tag{17}$$

where $\sigma > 0$ and $q \geq 0$.

5.6. Calculation of the criteria weights

Definition 8. The weights of the criteria can be calculated as follows:

$$S_i = \frac{a + 4b + c}{6} \tag{18}$$

where S_i represents the score values of the criteria. a, b, and c represent the values of lower, middle, and upper of triangular fuzzy numbers.

5.7. Ranking results

In this study, a q-ROF MABAC methodology under the fuzzy Einstein operator is applied to rank the alternatives. The steps of the proposed model are shown in Fig. 22. This study evaluates nine alternatives for selecting the best case based on seven criteria. The hierarchy of the E-DLT DM problem is illustrated in Fig. 21.

To calculate the weight coefficients of the criteria, the steps of type-I were used using fuzzy triangular numbers. The box-plot representation of the fuzzy weights of criteria is depicted in Fig. 23. It can be seen that Cybersecurity (C_4) and Interoperability (C_2) are the most important criteria in the DM model. It is also observed that the Energy Efficiency and Contribution to the UN SDG (C_6) and the Legal and Legislative Framework Maturity (C_7) are the least important criteria.

The score values are calculated using the steps of q-ROF based MABAC under fuzzy Einstein operator as shown in Fig. 22. The final values of alternatives for each criterion are presented in Table 1. Based on the integrated model, the ranking of alternatives results in the $A_7 > A_8 > A_1 > A_9 > A_3 > A_5 > A_2 > A_6 > A_4$ in that order from the best to the worst option.

Some parameter analyses were performed to check the stability of the results. Fig. 24 shows the changes in the parameter of σ that is from the interval $1 \leq \sigma \leq 100$. It can be seen that there was no change in the order of alternatives. The results indicate that alternative $A7$ is the best alternative.

In the second scenario, the impact of ϖ on the alternative was investigated. Fig. 25 shows the changes in the parameter of ϖ (MABAC parameter) that is from the interval $0.5 \leq \varpi \leq 1$. It can be seen that $A7$ is the best alternative.

6. Discussion

6.1. Interpretation of results and findings

Employing a multi-criteria DM methodology based on the fuzzy Einstein-based DM approach offers an exhaustive evaluation and ranking of diverse energy DLT use cases. This method enhances the DM

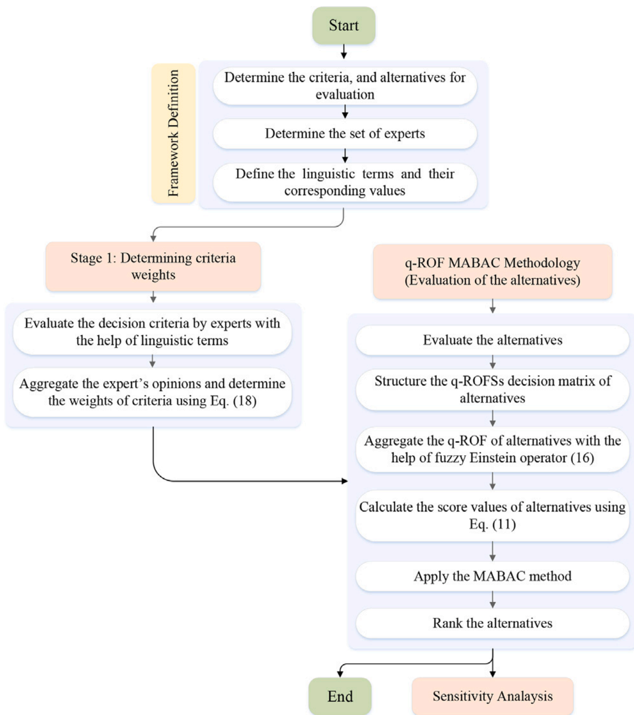

Fig. 22. The flowchart of the proposed methodology.

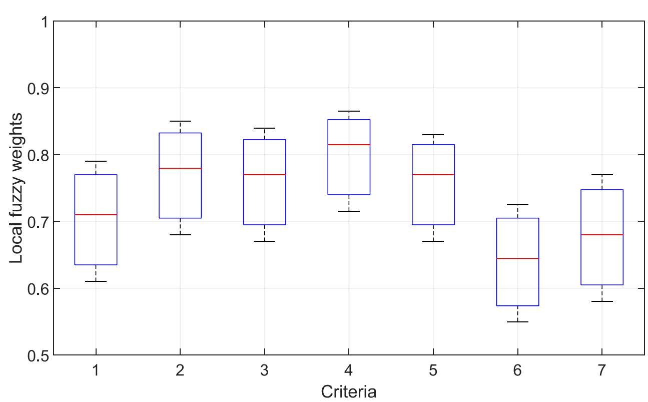

Fig. 23. Local fuzzy weights of criteria.

Table 1
The overall values of alternatives.

Alternatives	Overall values	Rank
A1: Grid and market transactions	0.322	3
A2: Green certificates and carbon trading	−0.179	7
A3: Metering, billing, and data access	0.245	5
A4: Cryptocurrencies, tokens and startup fundraising	−0.562	9
A5: IoT, smart devices, and asset management	−0.118	6
A6: Energy financing	−0.261	8
A7: Grid management and flexibility/grid services	0.420	1
A8: P2P, local and regional energy trading	0.363	2
A9: e-Mobility	0.276	4

process for enterprises, standardization organizations, researchers, and governmental entities. Utilizing this proposed method enabled the prioritization of the most fitting options out of nine alternative use cases based on seven criteria. The DM strategy incorporates various qualitative and quantitative criteria by gathering expert opinions via specialized surveys, ensuring a broad representation of expert insights. The outcomes of this model pinpointed the A7 (Grid management and flexibility/grid services scenario) as the foremost choice. The fuzzy Einstein-based DM model identifies scalability, transaction speed, and

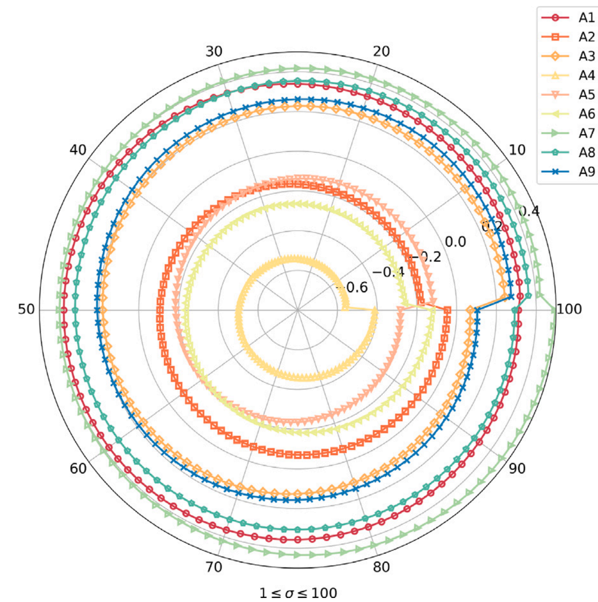

Fig. 24. The influence of σ on change of alternatives.

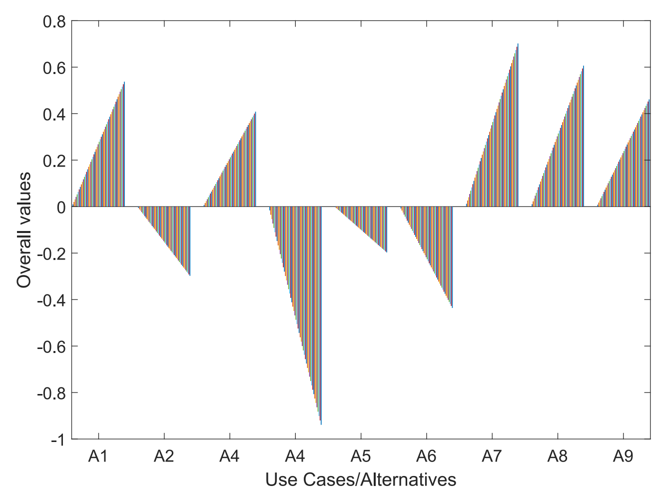

Fig. 25. The Influence of ϖ on change of alternatives.

cybersecurity as the most important criteria for DM in the power and energy sector.

To interpret these results and findings, it is essential to understand the methodology used and the specific criteria that were evaluated. Altering the weightings of criteria does not impact the ranking order of energy use cases in the blockchain system, indicating the robustness of the fuzzy Einstein-based DM model.

Overall, the interpretation of results and findings should be based on a thorough understanding of the methodology used, the specific criteria evaluated, and the context of the study or analysis. It is also important to consider any limitations or potential biases in the data or methodology. By following these best practices, researchers and analysts can ensure their interpretations are accurate and reliable.

6.2. Industrial and academic reflections

The paper explores the use of DLT in the energy sector through both industrial and academic perspectives. The authors conduct a thorough joint literature and market survey, employing a multi-criteria DM approach to rank potential energy use cases for DLT. The discussions on DLT in the energy sector encompass grid management, P2P energy trading, e-mobility, transactive energy systems, and other relevant aspects.

Considerations like scalability, transaction speed, cybersecurity, energy efficiency, and legal frameworks are among the crucial criteria used for DM. The content advocates for DLT's potential benefits in the energy industry, emphasizing its role in maximizing renewable energy utility, economic viability, and industrial efficiency.

The paper maps out existing energy-blockchain companies and promising applications, leaving the door open for further evolution and regional diversification of new use cases.

The proposed fuzzy Einstein-based DM approach aids in evaluating and prioritizing energy use cases with blockchain, fostering collaboration for a sustainable ecosystem. The USA, Germany, and Switzerland are the top three countries leading in blockchain projects for power and energy in terms of the scope of this study.

The findings underscore the significance of criteria like scalability, transaction speed, and cybersecurity in DM for the power and energy sector. While the paper recognizes the substantial potential of DLT in the energy sector, it stresses the need for a comprehensive study that incorporates both industrial and academic viewpoints to identify realistic and feasible use cases.

Prioritizing energy use cases through blockchain can enhance stakeholder collaboration and improve investment decision success. Decision-makers in standardization, investment optimization, and determination of the enterprise or policy-making strategy options can also use such a ranking of use cases.

The paper also discusses the challenges and opportunities of blockchain technology in energy applications, emphasizing the necessity of real-world implementations and realization pathways via prioritizing the use cases.

6.3. The advantages and limitations of the model

Despite the obvious advantages of the proposed model, there are certain limitations of the proposed model. The proposed fuzzy Einstein-based decision making approach can effectively uncertainty or ambiguous information; however, it is unlikely to process neutral and false information. Therefore, in future research, the proposed model can be improved by applying intuitionistic fuzzy or neutrosophic. The extension of the proposed model to other uncertainty theories aims to enable the processing of complex information. This can also expand the possible application areas of the proposed model.

6.4. Recommendations

This proposes a three-layer methodology for identifying the most realistic and feasible energy use scenarios where DLT can be applied. The methodology includes literature and market surveying supported by using DM and integrated expert surveying. The proposed method can successfully be used to normalize the outcomes. In contrast, coming up with some conclusions only by relying on the literature reviews and surveys will not be able to deliver normalized and reliable results. For instance, if we had only used the literature reviews, the most popular use case would have been P2P energy trading since this is the most frequently published topic in this area. In fact, the expert opinion and the outcomes of this work demonstrate some different results. According to the findings, the most promising use case is grid management and flexibility/grid services instead of P2P energy trading. This finding is also supported by the market survey, which shows that most P2P energy trading use case-related start-ups no longer exist after three to five years of market existence.

Hence, the paper suggests that researchers and practitioners in the energy sector should monitor on emerging start-up companies in the energy DLT field and use a two-fold stage framework to identify the most promising energy DLT use cases by sorting them in terms of importance. The ranking of such use cases is based on the number of occurrences. The paper also recommends that the power and energy sector should implement DLT to maximize the utility of renewable energy resources, create added value, and increase industrial efficiencies.

The paper proposes a DM algorithm based on a q-ROF-based MABAC under a fuzzy Einstein operator. This algorithm is supported by expert opinion via surveys that will be conducted by academia and industry. The paper also suggests that further research on q-ROFs could help to refine and improve DM processes in the energy sector. The paper recommends that researchers and practitioners in the energy sector should consider the fuzzy Einstein-based DM approach to evaluate and rank energy use cases that incorporate blockchain, as it provides a comprehensive assessment of their value and potential impact. Finally, the paper suggests that researchers should test and validate the fuzzy Einstein-based DM model against alternative DM models and existing approaches from the literature to ensure its consistency and reliability.

The paper recommends that policymakers and industry stakeholders support emerging start-up companies in the energy DLT field to encourage innovation and growth. The paper notes that public charging infrastructure is scarce for EVs, a significant barrier to customer adoption. Therefore, it is recommended that policymakers and industry stakeholders should increase investment levels in EV charging infrastructure to encourage the rapid adoption of EVs using emerging technologies like DLT. The paper also notes that public acceptance of blockchain technology is crucial for its adoption in the energy sector. Therefore, it is recommended that policymakers and industry stakeholders should increase public awareness and education about blockchain technology to encourage its acceptance and adoption.

6.5. Outlook

The paper explores future developments and advancements in the use of DLT in the energy sector, emphasizing the need to identify promising DLT use cases. It proposes a framework for this purpose and underscores the potential of blockchain in the energy sector. Despite these opportunities, challenges like the absence of standardization and interoperability among blockchain platforms persist. The paper recommends collaborative efforts among industry stakeholders to establish common standards and protocols, enabling more informed DM for companies, standardization bodies, and government authorities in their operations, including investment decisions.

Scalability is crucial for implementing DLT in the energy sector. Congestion threatens efficiency with rising transactions. The industry focus should shift to developing scalable solutions. Designing the entire process and DLT infrastructure around the use of on-chain data silos is a key consideration. Improved DLT infrastructure is anticipated, which will more effectively address potential scalability challenges in the future.

When identifying and developing high-potential use cases, energy, political, legal, technological, economic, and environmental factors must be considered. Policymakers are expected to meet the demands of new digital ecosystems, such as those based on DLT in the energy sector. Consequently, new regulations in this field are anticipated in the future. AI is a vital emerging technology reshaping various industries. Integrating AI with blockchain technology offers thrilling prospects for enhancing cross-sector collaboration within the energy sector.

7. Conclusions and outlook

The paper explores advancing DM frameworks within the power and energy sector through the utilization of DLT. Identifying high-potential energy DLT use cases necessitates a comprehensive study considering various aspects like energy, legislation, regulation, technology, economic implications, and environmental challenges.

The methodology comprises three layers: literature and market surveying, DM and expert surveying, and normalization and comparative analysis. Additionally, the paper introduces a two-stage framework aimed at pinpointing the most promising energy DLT use cases, prioritizing them based on importance. The initial stage involves an exhaustive literature and market survey of startup companies, projects, and academic studies in energy DLT. However, the most influential factor in use cases might be determined by such a methodology.

The authors suggest a q-ROF-based MABAC under a fuzzy Einstein operator to select the most suitable alternative among nine use cases. The outcomes from the techno-economic study deliver crucial inputs to their innovative DM algorithm, which utilizes expert surveying.

The unique contribution of this work lies in its multi-layered methodology that bridges academic rigor with real-world industrial validation. Unlike prior reviews that often present fragmented or overly optimistic portrayals of blockchain's potential, this study introduces a normalization mechanism to filter hype and focus on scalable, technically feasible, and policy-relevant solutions. By incorporating expert opinion and advanced fuzzy logic models, the proposed framework offers a replicable and adaptable approach for evaluating emerging technologies in energy systems.

The proposed decision-making algorithm, coupled with expert surveying and the q-ROF-based MABAC under the fuzzy Einstein operator, constitutes a substantial contribution to the field. It provides a thorough overview of the research methodology, essential background on DLT, and an extensive exploration of blockchain-based use cases in the energy sector. The demonstrated framework for identifying promising energy DLT use cases is also a valuable contribution, accompanied by a comprehensive comparative analysis encompassing both academic and industrial perspectives. This offers a forward-thinking perspective covering technical, economic, and energy policy aspects.

Moreover, the proposed framework helps to filter over hyped claims and provides a robust, evidence-based tool for researchers, industry professionals, and policymakers to support strategic decision-making for the adoption of DLTs within the energy system domain. The outcomes of this work can serve as a reference in the field of energy blockchain, representing one of the most comprehensive studies that simultaneously covers industrial and academic verticals.

Lastly, governmental authorities involved in policy development or the strategic allocation of research funding in this domain can leverage this work to ensure informed decision-making. Standardization bodies such as IEEE SA may also utilize the findings to prioritize efforts related to guidelines and standards. Finally, startups and venture capitalists supporting innovation in the energy blockchain space can use this document as a guide to identify the most promising use cases—relying on evidence and analysis rather than academic hype alone.

While this study provides a comprehensive evaluation framework for blockchain use cases in the energy sector, several important directions remain for future research. First, longitudinal and cross-sectoral studies are needed to assess the long-term performance, interoperability, and regulatory resilience of DLT implementations, especially in the context of dynamic grid modernization and energy market reforms. Second, the integration of blockchain with emerging digital technologies — particularly AI, generative AI, digital twins, and edge computing — offers promising pathways for developing intelligent, autonomous, and adaptive energy systems. These synergies could significantly enhance forecasting accuracy, real-time control, and decentralized decision-making in complex cyber–physical energy environments. Third, advances in quantum computing will likely challenge the cryptographic foundations of current blockchain systems, necessitating proactive research into quantum-resilient DLT architectures. Moreover, the development of energy blockchain systems must increasingly account for digital privacy and data governance, especially under evolving regulatory frameworks such as the GDPR, the EU AI Act, and sector-specific cybersecurity requirements. Lastly, future work should refine decision-making models by incorporating dynamic weighting mechanisms, explainable AI methods, and real-time data streams to improve practical deployment and stakeholder engagement in operational energy ecosystems.

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.

Acknowledgments

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Appendix A. List of acronyms

Acronyms in alphabetical order

AI	Artificial Intelligence.
AMI	Advanced Metering Infrastructure.
AML	Anti-Money Laundering.
BoD	Benefit of Doubt.
BWM	Best–Worst-Method.
CAPEX	Capital Expenditures.
DC	Direct Current.
DCIE	Data Center Infrastructure Efficiency.
DDoD	Distributed Denial of Service.
DEA	Data Envelopment Analysis.
DER	Distributed Energy Resource.
DG	Distributed Generation.
DLT	Distributed Ledger Technology.
DM	decision-making.
DoS	Denial-of-Service.
DR	Demand Response.
DSO	Distribution System Operator.
EV	Electric Vehicle.
EWF	Energy Web Foundation.
FDH	Free Disposable Hull.
FPP	Federated Power Plant.
GC	Green Certificate.
HEMS	Home Energy Management Systems.
ICO	Initial Coin Offering.
IFS	Intuitionistic Fuzzy Set.
INATBA	International Association of Trusted Blockchain Applications.
IoT	Internet-of-Things.
IVq-ROF	Interval Valued q-Rung Orthopair Fuzzy.
KYC	Know Your Customer.
LCOE	Levelized Cost of Electricity.
LEM	Local Exchange Model.
LES	Layered Energy System.
LV	Low Voltage.
M2M	Machine-to-Machine.
MABAC	Multi-Attributive Border Approximation.
MCDM	Multi Criteria Decision Making.
MCOCS	Multi Criteria Optimization and Compromise Solution.
ML	Machine Learning.
MV	Medium Voltage.
NaS	Nothing-at-Stake.
OPEX	Operational Expenditures.
P2P	Peer-to-Peer.
P2SH	Pay-to-Script-Hash.

PIPRECIA	Pivot Pairwise Relative Criteria Importance Assessment.
PoC	Proof-of-Concept.
PoG	Proof-of-Generation.
PoRE	Proof of Realistic Energy.
PoS	Proof-of-Stake.
PoW	Proof-of-Work.
PUE	Power Usage Effectiveness.
PV	Photovoltaic.
q-ROF	q-rung Orthopair Fuzzy.
REC	Renewable Energy Certificate.
REM	Regional Exchange Model.
RES	Renewable Energy Source.
SCM	Supply Chain Management.
SE	Sharing Economy.
STO	Secure Token Offering.
TGC	Tradable Green Certificate.
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution.
TPS	Transactions per Second.
TSO	Transmission System Operator.
TTP	Trusted Third Parties.
UN SDG	United Nations Sustainability Goals.
V2G	Vehicle-to-Grid.
VPP	Virtual Power Plant.
WASPAS	Weighted Aggregated Sum Product Assessment.
WC	White Certificate.

Table B.2
Characterization of initiatives, use cases, and governance/regulatory frameworks (Part 1).

			DLT Initiatives				Use Cases									Governance					
#	Reference	Country	Government-Sponsored Lab/Research	Academic Research	Utility Project	Start-up	Cryptocurrencies, Tokens and Startup Fundraising	P2P, Local and Regional Energy Trading	Metering, Billing, and Data Access	Energy Financing	Grid and Market Transactions	e-Mobility	IoT, Smart Devices, Automation and Other Technical	Green Certificates and Carbon Trading	Grid Management and Flexibility/Grid Services	Regulation	General Purpose and Consortia	Multi-National Conglomerate	National Conglomerate	Non-Partisan/Non-Profit	New Participant
1	AGL Energy [175]	Australia			✓			✓													
2	Aizu Laboratories [145]	Japan				✓					✓	✓									
3	Alastria [222]	Spain															✓			✓	
4	Alectra [140]	Canada			✓						✓				✓						
5	Allgauer Uberlandwerk [141]	Germany			✓			✓			✓				✓						
6	Alpiq [143]	Switzerland			✓						✓		✓		✓						
7	ASTRN Energy [151]	Australia				✓	✓	✓		✓			✓								
8	Bankymoon [272]	South Africa				✓		✓	✓												
9	Bittwatt [273]	Singapore				✓		✓													
10	Blockchain Futures Lab [274]	USA															✓			✓	
11	Blockchain Research Lab [275]	Germany															✓			✓	
12	BlockLab [276]	Netherlands			✓												✓				
13	CarbonX [277]	Canada				✓								✓							
14	Car eWallet [278]	Germany			✓							✓									
15	Conjoule [279]	Germany				✓		✓													
16	ConsenSys [280]	USA				✓		✓													
17	Clearwatts [281]	Netherlands				✓				✓											
18	DAO IPCI [282]	Russia				✓								✓						✓	
19	Data Gumbo [283]	USA				✓							✓								
20	Dena [284]	Germany																	✓		✓
21	E7 Venture [97]	USA											✓								
22	Elbox [285]	Switzerland			✓			✓													
23	ElectriCChain [286]	Andorra											✓							✓	
24	Electrify [287]	Singapore			✓			✓			✓										
25	Electron [288]	UK				✓		✓							✓						
26	Enel X e-Mobility [134]	UK			✓							✓									
27	Eneres [289]	Japan			✓			✓			✓				✓						
28	Energo Labs [290]	China				✓		✓				✓									
29	Energy21 [212]	Netherlands			✓			✓			✓				✓						
30	Energy Blockchain Labs Inc. [291]	China			✓									✓							
31	Energy Web Foundation [292]	Switzerland									✓						✓			✓	
32	Enervalis [293]	Belgium			✓						✓				✓						
33	Enervalis [293]	Belgium			✓						✓				✓						
34	ENGIE [294]	France			✓				✓												
35	Equigy [218]	Netherlands			✓						✓			✓							
36	EU Blockchain Observatory [295]	EU															✓		✓	✓	
37	Eurelectric [296]	EU															✓		✓	✓	
38	Everty [297]	Australia				✓						✓									
39	Evolution Energie [298]	France				✓		✓													
40	General Electric [299]	USA																✓			

Table B.3
Characterization of initiatives, use cases, and governance/regulatory frameworks (Part 2).

			DLT Initiatives				Use Cases									Governance					
#	Reference	Country	Government-Sponsored Lab/Research	Academic Research	Utility Project	Startup	Cryptocurrencies, Tokens and Startup Fundraising	P2P, Local and Regional Energy Trading	Metering, Billing, and Data Access	Energy Financing	Grid and Market Transactions	e-Mobility	IoT, Smart Devices, Automation and Other Technical	Green Certificates and Carbon Trading	Grid Management and Flexibility/Grid Services	Regulation	General Purpose and Consortia	Multi-National Conglomerate	National Conglomerate	Non-Partisan/Non-Profit	New Participant
41	Green Energy Wallet [300]	Germany				✓						✓			✓						
42	Greeneum [301]	Israel				✓		✓			✓				✓						
43	Grid+ [302]	USA				✓					✓										
44	Grid Singularity [303]	Germany				✓								✓	✓						
45	Guardtime & Intrinsic-ID [304]	USA			✓								✓								
46	Hive Power [305]	Switzerland				✓									✓						
47	IBM & Linux Foundation [306]	USA															✓			✓	
48	ImpactPPA [307]	USA			✓			✓			✓				✓						
49	LO3 Energy [161]	USA				✓		✓			✓										
50	MotionWerk [133]	Germany				✓						✓									
51	M-PAYG [308]	Denmark				✓			✓	✓											
52	MyBit [309]	Switzerland			✓		✓			✓			✓								
53	Nasdaq [310]	USA												✓							
54	OLI [311]	Germany			✓			✓					✓		✓						
55	OMEGAGrid [214]	USA			✓			✓			✓				✓						
56	Oursolargrid [312]	Germany			✓			✓			✓										
57	Oxygen Initiative [259]	USA				✓						✓									
58	PONTON [139]	Germany			✓			✓			✓										
59	Poseidon [313]	Switzerland												✓						✓	
60	Powerledger [94]	Australia				✓		✓			✓	✓	✓	✓	✓						
61	Powerpeers [314]	Netherlands				✓		✓			✓										
62	PROSUME [215]	Italy				✓		✓			✓	✓			✓						✓
63	PRTI [315]	USA				✓	✓														✓
64	Pylon Network [316]	Spain				✓		✓	✓												
65	Restart Energy [317]	Switzerland			✓			✓		✓											
66	Share & Charge [318]	Switzerland				✓						✓								✓	
67	Solar Bankers [95]	Singapore				✓		✓													
68	Sonnen [217]	Germany				✓		✓							✓						
69	Spectral [319]	Netherlands			✓			✓			✓				✓						
70	STROMDAO [320]	Germany				✓				✓											
71	Sunchain [321]	France				✓					✓	✓									
72	SunContract [322]	Slovenia				✓		✓													
73	Sun Exchange [152]	South Africa				✓	✓			✓											✓
74	Sunverge [208]	USA				✓					✓				✓						
75	TenneT [216]	Netherlands			✓										✓						
76	TOBLOCKCHAIN [323]	Netherlands			✓			✓					✓								
77	Vector [324]	New Zealand			✓			✓			✓										
78	Veridium Labs [325]	Hong Kong					✓							✓							
79	Verv [96]	UK				✓		✓					✓								
80	Volt Markets [326]	USA				✓		✓					✓	✓							

Appendix B. Tables

See Tables B.2–B.11.

Data availability

The utilized data is available in the manuscript at given tables and is fully open.

Table B.4
Characterization of initiatives, use cases, and governance/regulatory frameworks (Part 3).

			DLT Initiatives				Use Cases									Governance					
#	**Reference**	**Country**	Government-Sponsored Lab/Research	Academic Research	Utility Project	Startup	Cryptocurrencies, Tokens and Startup Fundraising	P2P, Local and Regional Energy Trading	Metering, Billing, and Data Access	Energy Financing	Grid and Market Transactions	e-Mobility	IoT, Smart Devices, Automation and Other Technical	Green Certificates and Carbon Trading	Grid Management and Flexibility/Grid Services	Regulation	General Purpose and Consortia	Multi-National Conglomerate	National Conglomerate	Non-Partisan/Non-Profit	New Participant
81	WePower [150]	Lithuania				✓			✓												✓
82	Wien Energie [153]	Austria			✓			✓	✓	✓											
83	RIDDLE & CODE [154]	Austria				✓		✓	✓	✓											
84	Wipro [232]	India																	✓		
85	Wirepas [327]	Finland			✓								✓								
86	Wuppertaler Stadtwerke [177]	Germany			✓				✓	✓											
87	XinFin [172]	Singapore			✓		✓													✓	
88	Andoni et.al. [13]	UK		✓																	
89	Northern Power Grid [98]	UK			✓			✓							✓						
90	Deloitte [219]	UK						✓	✓												
91	CNE [220]	Chile			✓			✓	✓						✓						
92	Khatoon, Asma [221]	Ireland		✓																	
93	Alastria [222]	Spain			✓			✓	✓		✓		✓		✓						
94	Allen et.al. [223]	Australia		✓						✓											
95	Davidson et.al. [224]	Australia		✓						✓											
96	de Oliveira et.al. [225]	Australia		✓																	
97	Johanson et.al. [226]	Sweden		✓																	
98	Monoghan et.al. [227]	Ireland		✓																	
99	Oviatt et.al. [228]	USA		✓																	
100	Gaur et.al. [229]	USA		✓																	
101	U.S. DOE [114]	USA	✓						✓		✓		✓		✓						
102	Aderibole et al. [210]	USA		✓																	
103	Guerrero et al. [200]	Spain		✓																	
104	Mylrea et al. [54]	USA		✓				✓	✓		✓		✓		✓						
105	M. Foti & M. Vavalis [202]	Greece		✓							✓				✓						
106	Sanseverino et al. [203]	Italy		✓							✓				✓						
107	Niesse et al. [204]	Germany		✓					✓		✓				✓						
108	Apostolopoulou et al. [205]	USA		✓							✓				✓						
109	Musleh et al. [206]	Australia		✓																	
110	Kumari et al. [201]	India		✓				✓					✓								
111	Stekli et al. [156]	USA		✓						✓											
112	Halden et al. [43]	Norway		✓						✓											
113	Cali et al. [44]	Norway		✓						✓											
114	Schulz et al. [157]	Netherlands		✓						✓											
115	Harwick et al. [158]	USA		✓						✓											
116	Judge et al. [99]	Pakistan		✓									✓								
117	Serrano et al. [102]	UK		✓									✓								
118	Singh et al. [103]	Rep. of Korea		✓				✓					✓								
119	Yi et al. [107]	China		✓									✓								
120	Sarac et al. [108]	Serbia		✓				✓					✓								

Table B.5
Characterization of initiatives, use cases, and governance/regulatory frameworks (Part 4).

			DLT Initiatives				Use Cases									Governance					
#	Reference	Country	Government-Sponsored Lab/Research	Academic Research	Utility Project	Startup	Cryptocurrencies, Tokens and Startup Fundraising	P2P, Local and Regional Energy Trading	Metering, Billing, and Data Access	Energy Financing	Grid and Market Transactions	e-Mobility	IoT, Smart Devices, Automation and Other Technical	Green Certificates and Carbon Trading	Grid Management and Flexibility/Grid Services	Regulation	General Purpose and Consortia	Multi-National Conglomerate	National Conglomerate	Non-Partisan/Non-Profit	New Participant
121	Lombardi et al. [109]	UK		✓				✓					✓								
122	Jain et al. [101]	India		✓				✓					✓								
123	Casquiço et al. [100]	Portugal		✓				✓					✓								
124	Hu et al. [104]	UK		✓									✓								
125	Wu et al. [105]	China		✓									✓								
126	Yurchenko et al. [124]	Germany		✓					✓				✓								
127	Houda et al. [125]	Canada		✓					✓				✓								
128	E.C. JRC [117]	Italy	✓						✓												
129	Dena [118]	Germany	✓						✓												
130	Ochôa et al. [126]	Brazil		✓					✓												
131	Ertz et al. [162]	Canada		✓			✓			✓	✓										
132	Duong et al. [171]	Vietnam		✓			✓			✓											
133	Ghosh et al. [171]	India		✓			✓														
134	Lo et al. [167]	UK		✓			✓														
135	Sung [173]	Rep. of Korea		✓			✓														
136	Mehdinejad et al. [166]	Iran		✓			✓	✓													
137	Truby et al. [170]	Qatar		✓			✓														
138	Christidis et al. [180]	USA		✓				✓													
139	M. Foti M. Vavalis [179]	Greece		✓				✓													
140	Seven et al. [185]	Greece		✓				✓													
141	Pebbles Project [142]	Germany	✓					✓	✓		✓				✓						
142	Kumar et al. [84]	India		✓					✓				✓								
143	Fu et al. [86]	China		✓					✓				✓								
144	Kumar et al. [85]	India		✓					✓				✓								
145	Shari et al. [82]	Malaysia		✓					✓				✓								
146	Rodrigues [83]	Brazil		✓					✓		✓		✓								
147	Ammi et al. [89]	Saudi Arabia		✓					✓				✓								
148	Kolahan et al. [90]	Italy		✓					✓				✓								
149	Samuel et al. [91]	Pakistan		✓					✓		✓		✓								
150	Jayabalasamy et al. [92]	India		✓					✓				✓								
151	Zhang et al. [87]	China		✓					✓				✓								
152	Hua et al. [88]	UK		✓					✓				✓								
153	Gourisetti et al. [49]	USA		✓					✓		✓		✓		✓						
154	Sunspec Alliance [50]	USA		✓									✓								
155	Gourisetti et al. [51]	USA		✓							✓		✓		✓						
156	Gourisetti et al. [52]	USA		✓							✓				✓						
157	Mylrea et al. [53]	USA		✓							✓				✓						
158	Mylrea et al. [54]	USA		✓							✓				✓						
159	Gourisetti et al. [199]	USA		✓				✓	✓												
160	Wire Pass [327]	Finland				✓		✓	✓				✓								
161	Stedin Group [328,329]	Netherlands			✓			✓	✓		✓		✓								
162	Mihaylov et al. [330]	Belgium		✓				✓	✓	✓			✓								

Table B.6
Characterization of initiatives, use cases, and governance/regulatory frameworks (Part 5).

			DLT Initiatives				Use Cases									Governance					
#	Reference	Country	Government-Sponsored Lab/Research	Academic Research	Utility Project	Startup	Cryptocurrencies, Tokens and Startup Fundraising	P2P, Local and Regional Energy Trading	Metering, Billing, and Data Access	Energy Financing	Grid and Market Transactions	e-Mobility	IoT, Smart Devices, Automation and Other Technical	Green Certificates and Carbon Trading	Grid Management and Flexibility/Grid Services	Regulation	General Purpose and Consortia	Multi-National Conglomerate	National Conglomerate	Non-Partisan/Non-Profit	New Participant
163	Mahmud et al. [248]	USA	✓					✓	✓	✓			✓								
164	Chen et al. [247]	USA	✓					✓	✓	✓			✓								
165	Gajanur et al. [243]	USA	✓					✓	✓	✓			✓								
166	Bandara et al. [242]	USA		✓				✓	✓	✓			✓								
167	Kaur et al. [244]	USA	✓	✓				✓	✓	✓			✓								
168	Ali et al. [241]	USA	✓					✓	✓	✓			✓								
169	Cutler et al. [245]	USA	✓					✓	✓	✓			✓								
170	Wonjiga et al. [240]	USA	✓					✓	✓	✓			✓								
171	Ray, Brian. [239]	USA	✓					✓	✓	✓			✓								
172	Shah et al. [246]	USA	✓					✓	✓	✓			✓								
173	Dwyer et al. [246]	USA	✓					✓	✓	✓				✓							
174	Ahl et al. [16]	Japan		✓													✓				
175	Appasani et al. [18]	India		✓				✓	✓		✓	✓	✓		✓		✓				
176	Cantillo-Luna et al. [19]	Colombia		✓				✓	✓	✓	✓	✓	✓		✓		✓				
177	Yap et al. [20]	Malaysia		✓				✓				✓			✓		✓				
178	Al-Abri et al. [23]	Oman		✓				✓			✓						✓				
179	Cali et al. [24]	Norway		✓									✓				✓				
180	Merrad et al. [25]	Malaysia		✓													✓				
181	Lee et al. [26]	USA	✓														✓				
182	Waseem et al. [27]	Pakistan		✓				✓	✓		✓	✓	✓				✓				
183	Zhao et al. [28]	USA		✓													✓				
184	Wang et al. (2022) [70]	China	✓											✓							
185	Shih et al. [106]	Taiwan		✓									✓				✓				
186	Teimoori & Yassine [136]	Canada		✓								✓									
187	Qi et al. [137]	USA		✓								✓									
188	Wang et al. (2023) [159]	China		✓						✓											
189	Seven et al. [184]	Turkey		✓				✓													
190	Khan et al. [193]	Pakistan		✓				✓													
191	Okoye & Kim [194]	South Korea		✓				✓													
192	Haselbarth et al. [207]	Germany		✓											✓						
193	Machado et al. [127]	Brazil		✓				✓	✓				✓		✓						
194	Gao et al. [112]	Australia		✓									✓								
195	Syamala et al. [186]	India		✓				✓	✓				✓		✓						
196	Meng et al. [128]	USA		✓				✓	✓				✓		✓						
197	Faheem et al. [130]	Finland		✓				✓	✓		✓		✓		✓	✓					
198	Codur et al. [93]	Turkey		✓									✓								
199	Mishra et al. [110]	India		✓									✓								
200	Babaei et al. [209]	Iran		✓					✓				✓		✓	✓					
201	Shang et al. [209]	China		✓				✓	✓		✓		✓		✓	✓					
202	Erdeyandi et al. [188]	UK		✓				✓	✓		✓		✓		✓	✓					
203	Gurjar et al. [189]	India		✓				✓	✓		✓		✓		✓	✓					
204	Mahmud et al. [174]	Bangladesh		✓			✓									✓					
205	Pathak et al. [111]	India		✓									✓			✓					

Table B.7
Description of initiatives, use cases, and governance/regulatory frameworks (Part 1).

#	Reference	Country	Description
1	AGL Energy [175]	Australia	AGL Energy the Australian utility company has launched a virtual trial to test peer-to-peer energy trading system in Carrum Downs, a suburb of Melbourne, Victoria
2	Aizu Laboratories [145]	Japan	Aizu Computer Science Laboratories is involved in realizing blockchain-based virtual power plants (VPP) integrated with the grid
3	Alastria [222]	Spain	Alastria is the non-profit multisectorial consortium promoted by organizations and institutions for the establishment of a Public-Permissioned Blockchain/DLT infrastructure, supporting services that will be compliant with Spanish and EU regulatory and legal frameworks
4	Alectra [140]	Canada	Alectra in partnership with IBM and Interac have developed a blockchain-based transactive energy platform called GridExchange in which consumers can dispatch resources in real-time to meet utility needs
5	Allgauer Uberlandwerk [141]	Germany	Allgauer Uberlandwerk the German utility has collaborated with Siemens in developing a local electricity marketplace for peer-to-peer electricity trading based on blockchain. The market platform also supports flexible power from battery storage or controllable loads such as heat pumps or charging stations for electric vehicles
6	Alpiq [143]	Switzerland	Switzerland-based utility Alpiq in collaboration with the Swissgrid have launched a pilot project Equigy. The project aims to balance short-term fluctuations in the transmission grid with the support of small decentralized energy sources. Equigy uses blockchain technology and Internet of Things (IoT)
7	ASTRN Energy [151]	Australia	ASTRN Energy provides blockchain-based platform to design, organize and implement physical Solar Energy Power Plant projects and convert them to a digital Virtual Energy Project. ASSETRON tokens are used to stake into the Virtual Energy Project, which is finally converted to current market value
8	Bankymoon [272]	South Africa	South Africa-based Bankymoon has launched prepaid blockchain smart meter technology as a solution to electrical utilities struggling to collect revenue and African consumers lacking formal banking facilities
9	Bittwatt [273]	Singapore	Bittwatt provides a blockchain based smart solutions for energy supply, trading and billing
10	BlockchainFutures-Lab [274]	USA	The Blockchain Futures Lab at Institute for the Future is a research initiative focussed for identifying the opportunities and limits of blockchain technologies as well as their social, economic, and political impacts on individuals, organizations, and communities
11	Blockchain Research Lab [275]	Germany	The Blockchain Research Lab is a non-profit company from Hamburg, Germany whose aim is to promote blockchain research and publication of the results for the benefits of society [218]
12	BlockLab [276]	Netherlands	BlockLab deals with blockchain technology that focusses on energy and logistics industry. They are involved in training and capacity building through collaboration with international consortia, governing, research and academic organizations
13	CarbonX [277]	Canada	CarbonX is an organization committed to engaging millions of people in the fight against climate change by materially rewarding individuals for responsible carbon consumption. The idea behind CarbonX is to build awareness about carbon emissions by establishing a personal carbon trading exchange that leverages blockchain technology
14	Car eWallet [278]	Germany	Car eWallet is a mobility-marketplace to connect service providers with users making the electric mobility related services fully automated. Car eWallet is set up and supported by strong partnership of ZF (vehicle integration), UBS (financial transactions) and IBM (delivers the blockchain technology)
15	Conjoule [279]	Germany	Conjoule an Innogy spin-off provides a blockchain-based peer-to-peer energy trading platform to enable PV owners within the same region to interact with each other
16	ConsenSys [280]	USA	ConsenSys is the leading Ethereum-based blockchain provider, which uses blockchain technology to create (software) applications in decentralized system
17	Clearwatts [281]	Netherlands	Start-up Clearwatts deals with arranging contracts and financial settlements of complex power purchase agreements in renewable energy projects using scalable distributed databases
18	DAO IPCI [282]	Russia	DAO IPCI is a decentralized blockchain-based ecosystem for users to work with environmental assets, liabilities, and carbon market institutions
19	Data Gumbo [283]	USA	Data Gumbo provides Gumbonet the massively interconnected industrial smart contract network secured and powered by blockchain. Primarily focused for industrial automation of supply chain and sustainability measurement
20	dena [284]	Germany	The German Federal Energy Agency (dena) develops strategies for the applied energy transition, such as the integration of blockchain in the energy system
21	Elbox [285]	Switzerland	Elbox in collaboration with Axpo has created a product that can be used as a platform solution for the operation of a regional peer-to-peer marketplace that uses the blockchain for the proof of origin of each unit of energy sold
22	E7 Venture [97]	USA	E7 Ventures provides software systems for Internet-of-Things, and Blockchain-based transactive energy systems

Table B.8
Description of initiatives, use cases, and governance/regulatory frameworks (Part 2).

#	Reference	Country	Description
23	ElectriCChain [286]	Andorra	ElectriCChain in a non-profit organization that aims to accelerate IoT-Blockchain solution for solar energy derived projects
24	Electrify [287]	Singapore	Electrify is a retail electricity marketplace based in Singapore. Their Marketplace provides consumer to compare the energy options and Synergy provides a peer-to-peer energy trading platform
25	Electron [288]	UK	Electron provides a blockchain-based local distributed energy markets platform that enables peer-to-peer energy trading and grid management
26	Enel X e-Mobility [134]	UK	Enel X provides electric vehicle (EV) charging market with its JuiceNet-enabled smart grid EV charging solutions. JuiceNet enabled devices, such as the company's connected, high-power JuiceBox charging stations, maximize charging efficiency and speed while providing EV owners intuitive control and visibility
27	Eneres [289]	Japan	Eneres a Tokyo-based utility company has started demonstration experiments to realize virtual power plants (VPP) for demand side management and peer-to-peer electricity sharing among individual power consumers
28	Energo Labs [290]	China	Energo Labs is a Chinese start-up with the intent of creating a peer-to-peer platform for a distributed energy system using blockchain technology with a special focus on microgrids. They also work with peer-to-peer EV charging
29	Energy21 [212]	Netherlands	Energy21 in collaboration with Stedin [328] offers a new energy market model based on the layered energy system (LES) [329] solutions. LES enables a open market for flexibility and peer-to-peer energy trading
30	Energy Blockchain Labs Inc. [291]	China	Energy Blockchain Labs Inc. a Beijing-based collaborative initiative on energy and environment blockchain applications has partnered with IBM to create a carbon credit management platform that uses Hyperledger Fabric and smart contracts
31	Energy Web Foundation [292]	Switzerland	Energy Web Foundation is an open-source ecosystem focussed on building and promoting decentralized blockchain technology across the energy sector
32	Enervalis [293]	Belgium	Enervalis is the industrial partner of the NRGcoin project [213]. NRGcoin is a blockchain based reward mechanism for both production and consumption of renewable energy [330]
33	ENGIE [294]	France	ENGIE has collaborated with Ledger to develop the first blockchain hardware to measure the data at the source of green energy production (such as wind turbines, solar panels or hydropower) and will record it securely into the blockchain to be used for decentralized application
34	EnLedger [294]	USA	EnLedger is a startup company that uses an EnergyChain blockchain built for grid connected asset management, share/dividends tracking, and automated power exchange connectivity
35	EU Blockchain Observatory & Forum [295]	EU	European Union Blockchain Observatory and Forum is an initiative to accelerate blockchain innovation and the development of its ecosystem within the European Union
36	Eurelectric [296]	EU	Eurelectric an association of european electricity industry has launched an expert platform within its membership to investigate the potential of the blockchain technology across the electricity value chain including generation, trading, supply and networks
37	Everty [297]	Australia	A community based Electric Vehicle (EV) charging network that allows drivers and charging station operators to easily access and manage charging stations. Everty provides a cloud-based Software as a Service (SaaS) platform to companies installing EV charging infrastructure
38	Evolution Energie [298]	France	Evolution Energie provides expert energy management softwares to energy suppliers and industrials to manage and optimize their portfolio. Evolution Energie has collaborated with GE Digital to develop the blockchain-based energy sharing platform
39	General Electric [299]	USA	General Electric Research has formed a multi-disciplinary research team to begin exploring the application of Blockchain in their digital industrial manufacturing processes. Various blockchain-based projects are explored in their Forge Lab
40	Green Energy Wallet [300]	Germany	Green Energy Wallet is a German-based startup that uses blockchain to facilitate leasing of EV batteries and residential storage batteries to store renewable energy at peak production
41	Greeneum [301]	Israel	Greeneum uses a new token GREEN [331] to facilitate and local peer-to-peer energy trading and grant carbon credits and green certificates
42	Grid+ [302]	USA	Grid+ provides a blockchain-based platform to give consumers direct access to wholesale energy markets

Table B.9
Description of initiatives, use cases, and governance/regulatory frameworks (Part 3).

#	Reference	Country	Description
43	Grid Singularity [303]	Germany	Grid Singularity is an open source energy technology startup that simulates and operates interconnected grid-aware energy marketplaces. The company's platform is based on blockchain technology which assists in forecasting grid balancing, facilitating investment and trading of green certificates
44	Guardtime & Intrinsic-ID [304]	USA	Guardtime and Intrinsic-ID has collaborated together to deliver customer solutions combining Intrinsic-ID's SRAM Physical Unclonable Functions (PUFs) and Guardtime's Keyless Signature Infrastructure (KSI) Blockchain technology, providing a new level of security and governance for the IoT
45	Hive Power [305]	Switzerland	Hive Power provides a Software as a service (SaaS) for smart grid analytics to improve community self-consumption, and SaaS for flexibility to help energy suppliers and grid operators (DSOs and TSOs) to improve their operation and asset management
46	IBM & Linux Foundation [306]	USA	Linux Foundation has launched a open source project the Hyperledger Fabric to help drive up adoption rates for enterprise blockchain use case
47	ImpactPPA [307]	USA	ImpactPPA provides an Ethereum-based decentralized energy trading platform that enables consumer to pay for energy directly from the mobile device
48	LO3 Energy [161]	USA	LO3 Energy operates on blockchain-based platform the Pando which is recently updated onto the Energy Web Chain platform. Pando is provided as a white-label solution for utilities to streamline accounting for distributed energy resources (DERs) and create local energy marketplaces such as peer-to-peer energy trading for their customers
49	MotionWerk [133]	Germany	MotionWerk is involved in developing a blockchain-based e-Mobility community platforms to support an open and secure solutions and infrastructure for the mobility industry
50	M-PAYG [308]	Denmark	M-PAYG is an organization that provides pay as you go solar power options in developing nations. Their combined hardware and software solution allows low-income households in developing countries access to solar energy through small-scale mobile money payments
51	MyBit [309]	Switzerland	MyBit provides a decentralized exchange for IoT assets. It provides and ecosystem for IoT investment by enabling the rapid building, testing, and deployment of IoT assets management applications on the Ethereum Blockchain
52	Nasdaq [310]	USA	Nasdaq is a stock exchange and financial services company based in New York city. Nasdaq has acquired a majority stake in Puro.earth to develop a blockchain-based online carbon trading platform for offsetting credits, as well as carbon removal certificates
53	OLI [311]	Germany	OLI develops blockchain software and hardware components for the energy sector. The intelligent load management system OLI Move seamlessly works together with OLI Market, a trading system for flexibility and energy. Furthermore, OLI Label and OLI Meter are integrated without barriers, to forms a revolutionizing system of handling, trading, and monitoring energy
54	OMEGAGrid [214]	USA	OMEGAGrid is a peer-to-peer blockchain energy platform for utilities with a special focus on grid balancing
55	Oursolargrid [312]	Germany	Developer of a blockchain-enabled community exchange for solar energy
56	PONTON [139]	Germany	PONTON provides an Enerchain a blockchain-based framework for peer-to-peer wholesale energy trading platform that enables OTC energy trading in power and gas products such as standardized spot and forward contracts
57	Poseidon [313]	Switzerland	Poseidon provides platform to track, trade, and retire carbon credits transparently through blockchain technology, specifically the Stellar blockchain
58	Powerledger [94]	Australia	Powerledger provides blockchain-based platform for peer-to-peer trading of energy, flexibility services and environmental commodities
59	Powerpeers [314]	Netherlands	Powerpeers is a community-based digital and interactive peer-to-peer energy trading marketplace where supply and demand for self-generated energy converge. The platform enables households to select electricity from specific sources, and share self-generated electricity with other peers within the community
60	PROSUME [215]	Italy	PROSUME offers a decentralized and self-regulated monitoring platform for peer-to-peer energy exchanges, EV management and grid balancing through demand response functions to empower individual prosumers and energy communities in a locally shared market
61	PRTI [315]	USA	PRTI provides paid tire disposal services. PRTI Thermal Demanufacturing process uses old tyres to generate energy. This generated energy is used to mine cryptocurrency
62	Pylon Network [316]	Spain	Decentralized energy market providing market signals and financial incentives, Pylon Network offer Pylon core as an open source decentralized communication protocol for energy data to facilitate and accelerate digitization of the energy sector and the energy transition
63	Restart Energy [317]	Switzerland	Restart Energy Innovative Technologies AG is a Swiss-based holding company offers a blockchain-based RED Platform which is the peer-to-peer energy trading marketplace that connects distributed energy resources like RES producers, consumers and prosumers while offering Supply-as-a-Service for energy retailers
64	Share&Charge [318]	Switzerland	Share&Charge is an open source electric vehicle (EV) charging protocol, that utilizes blockchain technology to provide solutions for the challenges of a fragmented Charge Point market

Table B.10
Description of initiatives, use cases, and governance/regulatory frameworks (Part 4).

#	Reference	Country	Description
65	Solar Bankers [95]	Singapore	Decentralized local energy market. The Solar Bankers peer-to-peer energy trading platform is currently being deployed and test in Izmir, Turkey
66	Spectral [319]	Netherlands	Spectral, a smart energy services company provides a blockchain-based decentralized energy system the Spectral Energy Exchange (SPEX) for peer-to-peer automated negotiation and settlement of energy and flexibility trading
67	STROMDAO [320]	Germany	STROMDAO is an open source software company that builds and operates a boutique blockchain network for energy market transactions
68	Sunchain [321]	France	Sunchain provides blockchain-based solutions to energy project developers and utilities for energy exchanges management, collective auto consumption, certification and green mobility
69	SunContract [322]	Slovenia	SunContract offers a decentralized energy trading platform. They are in the process of setting up a new P2P energy marketplace for dynamic pricing, and development of a P2P retail-level cross-border energy trading marketplace between different countries
70	Sun Exchange [152]	South Africa	South African-based startup allows international clients to buy remotely-located solar cells either with Bitcoin(BTC) or South African rand and then lease solar cells to power business and organizations in emerging markets
71	Sunverge [208]	USA	Sunverge provide utilities and solar providers the ability to aggregate solar batteries and other distributed energy resources into virtual power plants. Their VPP is then used for energy management and providing the grid services
72	TenneT [216]	Netherlands	TenneT and IBM have joined forces for two blockchain pilots in which they explore the use cases of blockchain in guaranteeing a continuous supply of electricity by balancing supply and demand
73	TOBLOCKCHAIN [323]	Netherlands	TOBLOCKCHAIN provides a peer-to-peer energy sharing platform the PowerToShare which allows energy producers and consumers to share energy. Blockchain IoT integration with the energy market is one of the key focus area of TOBLOCKCHAIN
74	Vector [324]	New Zealand	New Zealand energy and technology company Vector has collaborated with Australian blockchain energy company Powerledger to provide peer-to-peer energy trading platform allowing people to buy and sell power without using an electricity retailer
75	Veridium Labs [325]	Hong Kong	Veridium Labs is a blockchain-based carbon credit and natural capital marketplace that provides a transparent way for corporations, governments and individuals to acquire, trade and account for carbon footprints and offsets
76	Verv [96]	UK	Verv have introduced an energy management and predictive maintenance solution to detect the energy usage at the individual appliances level. This disaggregation for individual appliance recognition in turns forms the basis of the peer-to-peering energy trading platform
77	Volt Markets [326]	USA	Volt Markets is one of the notable startups providing energy origination, tracking, and trading platform. They disintermediate traditional energy markets and enable monitoring, managing, originating and trading energy and energy attributes in a peer-to-peer market on the Ethereum blockchain
78	WePower [150]	Lithuania	WePower provides a blockchain-based green energy financing and trading platform. It helps renewable energy producers to raise capital by issuing their own energy tokens which is subsequently traded through the platform either to purchase electricity or exchanged for cryptocurrencies
79	Wien Energie [153]	Austria	Wien Energie the Austria's largest utility provider has collaborated with Vienna-based blockchain interface company the RIDDLE&CODE to launch the blockchain-powered platform MyPower for the tokenisation of renewable assets. The platform enables consumers to participate in both energy consumption and production of green energy by tokenising solar photovoltaic (PV) assets and allowing consumers to purchase shares in PV plants across Austria
80	Wipro [232]	India	Wipro an Indian multinational conglomerate company has joined Hedera governing council [332] to provide decentralized governance model for blockchain. The council is focussed in developing the decentralized governance model for a public ledger
81	Wirepas [327]	Finland	Wirepas a global IoT enterprise company have collaborated with Energy Web Foundation to demonstrate the proof of concept that connects the IoT devices to the blockchain-based digital energy webchain on the consumer side or the grid edge
82	Wuppertaler Stadtwerke [177]	Germany	Wuppertaler Stadtwerke (WSW) the municipal energy supplier provides a blockchain-based trading platform the Tal.Markt, where customers can purchase their electricity from local green electricity providers and put together their own energy mix. Every transaction is carried out tamper-proof using blockchain technology
83	XinFin [172]	Singapore	XinFin is a hybrid and decentralized blockchain network for global trade and financial transactions

Table B.11
Status of start-up companies with DLT initiatives per October 2024.

#	Company Name	Status	Use Cases
2	Aizu Laboratories [145]	No news since 2021	Grid and Market Transactions , e-Mobility
7	ASTRN Energy [151]	Website down	Cryptocurrencies, Tokens and Startup Fundraising, P2P, Local and Regional Energy Trading, Energy Financing, IoT, Smart Devices, Automation and Other Technical
8	Bankymoon [272]	No news since 2017	P2P, Local and Regional Energy Trading, Metering, Billing, and Data Access
9	Bittwatt [273]	Active	P2P, Local and Regional Energy Trading
13	CarbonX [277]	Active	Green Certificates and Carbon Trading
15	Conjoule [279]	No news since 2018	P2P, Local and Regional Energy Trading
16	ConsenSys [280]	Active	P2P, Local and Regional Energy Trading
17	Clearwatts [281]	Active	Energy Financing
18	DAO IPCI [282]	Active	Green Certificates and Carbon Trading, Non-Partisan/Non-Profit
19	Data Gumbo [283]	Active	IoT, Smart Devices, Automation and Other Technical
25	Electron [288]	Active	P2P, Local and Regional Energy Trading, Grid Management and Flexibility/Grid Services
28	Energo Labs [290]	Website down	P2P, Local and Regional Energy Trading, e-Mobility
38	Everty [297]	Active	e-Mobility
39	Evolution Energie [298]	Active	P2P, Local and Regional Energy Trading
41	Green Energy Wallet [300]	No news since 2019	e-Mobility, Grid Management and Flexibility/Grid Services
42	Greeneum [301]	Active	P2P, Local and Regional Energy Trading, Grid and Market Transactions
43	Grid+ [302]	Active	Grid and Market Transactions
44	Grid Singularity [303]	Active	Green Certificates and Carbon Trading, Grid Management and Flexibility/Grid Services
46	Hive Power [305]	Active	Grid Management and Flexibility/Grid Services
49	LO3 Energy [161]	Website down	P2P, Local and Regional Energy Trading, Grid and Market Transactions
50	MotionWerk [133]	Website down	e-Mobility
51	M-PAYG [308]	Website down	P2P, Local and Regional Energy Trading, Metering, Billing, and Data Access
57	Oxygen Initiative [259]	No news since 2019	P2P, Local and Regional Energy Trading, Grid and Market Transactions
60	Powerledger [94]	Active	P2P, Local and Regional Energy Trading, Grid and Market Transactions
61	Powerpeers [314]	Active	P2P, Local and Regional Energy Trading, Grid and Market Transactions
62	PROSUME [215]	Active	P2P, Local and Regional Energy Trading, Grid and Market Transactions
63	PRTI [315]	Active	Cryptocurrencies, Tokens and Startup Fundraising
64	Pylon Network [316]	No news since 2021	P2P, Local and Regional Energy Trading, Metering, Billing, and Data Access
66	Share & Charge [318]	Active	e-Mobility, Non-Partisan/Non-Profit
67	Solar Bankers [95]	Website down	P2P, Local and Regional Energy Trading
68	Sonnen [217]	Active	P2P, Local and Regional Energy Trading, Grid Management and Flexibility/Grid Services
70	STROMDAO [320]	Active	Energy Financing
71	Sunchain [321]	Active	Grid and Market Transactions , e-Mobility
72	SunContract [322]	Active	P2P, Local and Regional Energy Trading
73	Sun Exchange [152]	Active	Cryptocurrencies, Tokens and Startup Fundraising
74	Sunverge [208]	Active	Grid and Market Transactions, Grid Management and Flexibility/Grid Services
75	TenneT [216]	Active	Grid Management and Flexibility/Grid Services
79	Verv [96]	Active	P2P, Local and Regional Energy Trading, IoT, Smart Devices, Automation and Other Technical
80	Volt Markets [326]	No news since 2016	P2P, Local and Regional Energy Trading, IoT, Smart Devices, Automation and Other Technical, Green Certificates and Carbon Trading
81	WePower [150]	Domain closed	Metering, Billing, and Data Access, New Participant
83	RIDDLE & CODE [154]	Active	P2P, Local and Regional Energy Trading, Metering, Billing, and Data Access, Energy Financing
161	Wire Pass [327]	Active	P2P, Local and Regional Energy Trading, Metering, Billing, and Data Access, IoT, Smart Devices, Automation and Other Technical

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