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Blockchain Research and Development Activities Sponsored by the U.S. Department of Energy and Utility Sector

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Abstract: This article provides an in-depth analysis of blockchain research in the energy sector, focusing on projects funded by the U.S. Department of Energy (DOE) and comparing them with industry-funded initiatives. A total of 110 funded activities within the U.S. power industry were successfully tracked and mapped into a newly developed categorization framework. This framework is designed to help research agencies to systematically understand their funded portfolio. Such characterization is expected to help them make effective investments, identify research gaps, measure impact, and advance technological progress to meet national goals. In line with this need, the proposed framework proposes a 2-D categorization matrix to systematically classify blockchain efforts within the energy sector.Under the proposed framework, the *Energy System Domain* serves as the primary classification dimension, categorizing use cases into 30 distinct applications. The second dimension, *Blockchain Properties*, captures the specific needs and functionalities provided by Blockchain technology. The aim was to capture blockchain's applicability and functionality: where and why blockchain? Principles behind the selection of the viewpoint dimensions were carefully defined based on consensus obtained through the Blockchain for Optimized Security and Energy Management (BLOSEM) project. The mapped results show that activities within the *Grid Automation*, *Coordination*, *and Control* (31.8%), *Marketplaces and Trading* (25.5%), *Foundational Blockchain Research* (19.1%), and *Supply Chain Management* (17.3%) domains have been actively pursued to date. The three leading specific use case applications were identified as *Transactive Energy Management* for *Marketplaces and Trading*, *Asset Management* for *Supply Chain Management*, and *Fundamental Blockchain* for *Foundational Blockchain Research.* The *Marketplaces and Trading* and *Retail Services Enablement* domains stood out as being favored by industry by a factor greater than 2 (2.3 and 2.6, respectively), yet there seemed to be little to zero investment from DOE. Approximately 76% of the total projects prioritized *Immutability*, *Identity Management*, and *Decentralization and/or Disintermediation* compared to *Asset Digitization and/or Tokenization, Automation*, and *Privacy and/or Anonymity*. The greatest discrepancies between DOE and industry were in *Asset Digitization and/or Tokenization* and *Automation*. The industry efforts (36% in *Asset Digitization/Tokenization* and 22% in *Automation*) was 14 times and 2.4 times, respectively, more intensive than the DOE-sponsored efforts, indicating a significant discrepancy in industry versus government priorities. Overall, quantifying DOE-sponsored projects and industry activities through mapping provides clarity on portfolio investments and opportunities for future research.

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1. Introduction

The current U.S. grid infrastructure struggles with the increasing integrations driven by distributed energy resources (DERs), Internet of Things (IoT) connected devices, smart meters, and other interconnected approaches to power generation and delivery. Some discontinuities exist in the energy communication network and a lack of data management tools in the existing centralized electric grid systems.

Coordinating DER systems at different scales and locations to meet regulated frameworks and policies is becoming more complicated because the interactions of multiple energy actors within decentralized marketplaces in response to a dynamic power supply and demand cannot be guaranteed and secured. Some DER systems are managed manually and locally between the energy producers or prosumers and the service retailers. These communications are difficult to coordinate due to poor integration, data management, and connectivity between the IoT systems and the existing electric grids; therefore, maintaining grid stability and safeguarding communications to support energy market analysis will be increasingly challenging. Thus, the U.S. Department of Energy (DOE) seeks to continually innovate and improve the electric grid by investing in cutting-edge technologies that will aid in the realization of efficient, reliable, and resilient infrastructure.

1.1. Blockchain in the Energy Sector

Emerging distributed ledger technologies (DLTs), such as blockchain, can be key enabling technologies to modernize the electric grid systems. Blockchain technologies can provide a more accessible data platform to connect decentralized energy transactions and cyber and physical energy assets with enhanced reliability, security, and immutability. These features are possible with distributed databases, smart business logics, known as "smart contracts", and consensus-driven activities with "trustless" protocols, such as those offered by blockchain.

Crossing organizational borders and multi-scale participation of all energy stakeholders in energy services and trading, including disparate DER owners, could be realized through blockchain without traditional intermediaries. The digitalization of the energy systems using blockchain can transform the current underlying processes to more active and transparent engagement in the energy sector without compromising privacy. Effective energy market management is vital to optimizing the value of the energy chain and to securing smooth operations and low-cost energy services. Effective energy management could remove reliance on third parties in transactive energy systems, reducing transaction cost by 20–40% [1,2].

Blockchain can serve as a digital ledger whose inherent properties can be leveraged to enable a wide variety of use case applications across energy production, transmission, and distribution. Blockchain development in the energy sector is relatively new compared to the business and economic sectors. Based on bibliometric analysis conducted on blockchain in technical journal publications, only 2% of 2451 tracked blockchain activities worldwide were reported for energy [3]. Although blockchain progress in the energy sector does not seem less than in other fields, power companies have started to invest in and collaboratively work on multiple blockchain projects to leverage blockchain functionalities for the smart environment, accelerating innovations for electric grid systems [1,4,5]. One main consideration of blockchain deployment is to solve longstanding issues in supply chain management. Blockchain could help facilitate proactive energy asset management, such as the integration of DERs and IoT devices, and enable transactive energy markets and trading platforms [2,6,7]. The global market for blockchain integration for microgrids in remote and grid-connected applications is projected to increase as much as 67.8% between 2019 and 2028 [8].

1.2. Background Study of Categorization of Blockchain Use Case

Requirements of blockchain functionalities are dominated by use case applications, which greatly vary depending on the issues to be solved. Potential use cases for data storage, registry, identity management, negotiation, and settlement have been widely discussed by blockchain researchers and developers. The Electric Power Research Institute (EPRI) has identified seven main categories for emerging use cases in the energy sector from their survey of U.S. and European utilities [7]. These categories were generally spread across *Customer Management*, *Decentralized Markets*, *Cybersecurity*, *DER Management*, and *Electric Vehicles* (EVs).

Meanwhile, the Energy Blockchain Consortium has listed approximately 18 potential use cases for blockchain deployment that are mainly relevant to power equipment manufacturers, independent system operators, and regional transmission operators for supply chain and logistics optimization [9,10]. The European Union Blockchain Observatory and Forum (EUBOF) has simplified potential use cases for energy under three big umbrellas: *flexibility services*, *energy attribute certificates trading*, and *digital identities for energy assets* [11]. The EUBOF report also presented examples on existing blockchain projects associated with electricity attribute certificates were also presented. Similarly, some blockchain experts also categorized use cases based on renewable energy applications according to ongoing and successful project demonstrations by companies [5,12]. The World Economic Forum, in conjunction with Stanford Woods Institute for the Environment and PricewaterhouseCoopers (PwC), identified more than 65 existing and emerging blockchain use cases for energy and environmental sustainability [13]. The focus of the assessment was to address environmental challenges, such as climate change, biodiversity loss, and water scarcity.

In addition to the evaluation of blockchain use cases from blockchain developers and consortiums, there are journal articles that have reviewed blockchain use cases in the energy sector. Some authors have conducted bibliometric analysis to comprehensively explore the pattern of the existing blockchain technical journal publications either across various scientific fields or specifically in the energy sector [3,14]. Statistical correlations were also used in the bibliometric analysis to draw some summaries on blockchain use cases and research and development (R&D) aspects according to the published research areas and interests [3,14]. Meanwhile, others have published an overview of blockchain, focusing on blockchain and use case development in energy by highlighting the existing R&D, activities, pilot demonstrations, and discussions of opportunities and challenges [4,15,16]. Broadly speaking, these use cases include applications that are relevant (to) energy tokenization and cryptocurrencies, peer-to-peer trading, wholesale energy trading, decarbonization and renewable reward programs, and other EVs.

1.3. Motivation of the Study

Due to the complexity and diversity of topics, redundancies in classifying potential use cases exist, but no systematic study has been done to objectively and uniformly categorize blockchain use cases in the energy sector [17]. An attempt to systematically categorize the use cases existed, but the categorization boundaries were set around specific scopes of the survey and thus was not wide ranging [1,14]. Some blockchain use cases were roughly simplified as overall applications in the energy sector, such as the reviews conducted by [4,16,18]. Meanwhile, some classifications focused on an explicit field of interest, such as applications for only renewable energy technologies for microgrid systems [19–21].

Inconsistencies in classifying blockchain use cases in the energy sector were also observed. The use cases were always independently evaluated based on separate analyses of stakeholder perspectives and the state of the art of blockchain R&D. There is a need to have a systematic framework and an inclusive list of blockchain use cases that could be used to map blockchain R&D efforts. A map of blockchain activities can help provide clarity on current portfolio investments, allow for assessments of R&D gaps and opportunities, and provide information that can be used to conduct coordinated and strategic funding decisions for future research efforts.

1.4. Contribution

To add significant value to the existing knowledge on blockchain use cases in the energy sector, this study develops a new categorization framework that can systematically group numerous blockchain R&D activities across two dimensions: (1) energy system domains with respective use case applications and (2) blockchain properties. This two-dimensional (2-D) framework can be used to define existing and emerging blockchain adoptions in the energy sector, including the blockchain functionalities that were most leveraged in each project reviewed. Without paying much consideration to the details of the blockchain construction, this 2-D framework seeks to answer the questions of *"where is blockchain being used?"* and *"why blockchain?"*, which can help observe the full portfolio of activities summarized in a clear and concise pattern.

This paper discusses the methodical approaches for the identification and categorization of the key blockchain use cases and properties in the energy sector. A longstanding, extensible framework can be established by introducing an organizational structure that is based on energy system domains, use case applications, and blockchain properties.

A comprehensive review of blockchain R&D activities was also conducted mainly within the scope of projects sponsored by DOE and U.S. power utilities. This review consists of more than 100 use cases in energy applications that exceeded the 2% publications tracked by [3]; however, little information is available that provides greater context for each individual research work and how it fits within the DOE portfolio of activities as a whole. The goal of this review was to present some insights into blockchain progress in the United States. By compiling and mapping these blockchain activities to the developed 2-D categorization matrix, **this study contributes to the blockchain body of knowledge in the energy sector by providing:**

1. A systematic and structured framework for use case categorization that can be used to record blockchain activities according to energy system domains and use case applications in one dimension and blockchain properties in another dimension.
2. A categorization mapping matrix of currently tracked blockchain use cases based on projects and publications within the scope of the DOE-sponsored R&D efforts and the U.S. utility demonstration projects, the distribution of current portfolio investments, and the areas of interest of blockchain applications.
3. Highlights of the most actively or less actively pursued blockchain activities, with the focus on energy system domains, use case applications, and blockchain properties.
4. Highlights on the existing gaps between DOE and U.S. utility industry activities based on the categorization mapping matrix.

1.5. Article Structure

The remainder of this paper is structured as follows: Section 2 presents an extensive review of DOE and industry-funded blockchain initiatives, highlighting their contributions and gaps being addressed for energy applications. Section 3 describes the proposed 2-D categorization matrix, categorizing use cases into six large categories of energy system domain and then identifying the key functions that blockchain fulfills.

Section 4 summarizes historical blockchain activities in both DOE and industry mapped into the developed 2-D categorization matrix. This section also presents a detailed analysis of the blockchain use cases based on activities by energy system domains and activities by blockchain properties. This analysis highlights the coordination and gaps between DOE and industry efforts. Sections 5 and 6 describe conclusions and some future work that would potentially help accelerate blockchain development and deployment (see Figure 1 for more details).

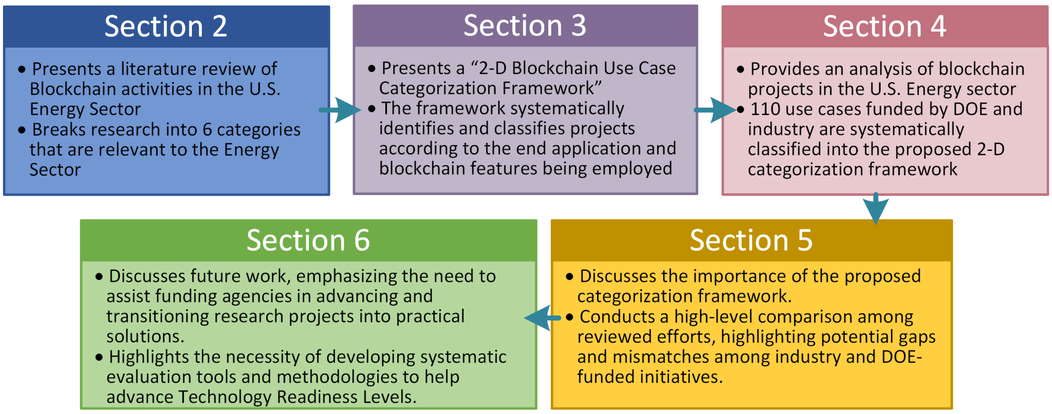

Figure 1. A graphical overview of the article structure.

1.6. Research Limitations

The work presented in this paper was funded by the U.S. DOE. The goal was to systematically analyze its funded portfolio in the blockchain/energy domain and to see how well these efforts aligned with industry interests and expectations. As a result, all reviewed articles had to either be funded by a U.S.-based source or be implemented within the U.S. Additionally, due to funding requirements, this article only includes publicly known projects that were funded and reported up to the fiscal year 2022, which ended on 30 September 2022.

Despite this funding-specific focus, the authors developed a comprehensive and reusable framework that systematically classifies blockchain projects in the energy sector, irrespective of the funding source. This framework allows systematic comparison of any funded project, making it a valuable tool for policymakers, independent consultants, and researchers in the field.

2. Literature Review of Blockchain Activities in the U.S. Energy Sector

DOE is dedicated to building a modern electric grid that employs cutting-edge technologies to supply abundant, low-cost energy in a highly resilient and reliable way to meet the nation's needs [22]. New technologies, such as DLTs and blockchain, pose a promising solution to a host of challenges currently facing various sectors within the bulk power system. Blockchain's inherent features of decentralization, immutability, integrity and data provenance can be used to enhance the security of energy systems by helping to protect data and critical infrastructure against an ever-evolving threat landscape.

This section presents some background on blockchain activities within DOE and U.S. power utilities. This review includes a collection of the existing and ongoing DOE research efforts that have been executed by 17 national laboratories, universities, and companies nationwide as well as a compilation of pilot demonstrations, beta tests, and other R&D efforts that are being conducted by the electric power industry.

2.1. Retail Services

Of the industry projects that have been identified, two were recognized to be relevant to EV smart contracts for renting, leasing, and purchase. In the first effort, Power Ledger and Silicon Valley Power use Power Ledger's Trace platform to track and measure credits in the Low Carbon Fuel Standard (LCFS). This pilot was done using solar panels and EV charging infrastructure in a multistory parking garage [23–25]. The second effort includes Électricité de France (EDF) and Sacramento Municipal Utility District (SMUD) EV charging. This activity was conducted by SMUD and EDF using Omega Grid's local electricity market software to coordinate EV charging with solar generation. Omega Grid uses a private, Python-based, Proof-of-Authority (PoA) solution with public settlement and embedded smart contract capability [26].

Another industry effort includes a collaborative pilot demonstration called "Charge Forward" between A Bayerische Motoren Werke AG (BMW) and Pacific Gas and Electric Company (PG&E) that seeks to incentivize drivers to charge their EV during hours when that grid has ample solar generation. This activity uses telematic data from BMW to cross-reference and use charging behavior with real-time energy mix data, and it provides customers with carbon credits that can be traded on California's marketplace to monetize their clean charging choices [27].

These industry examples show that blockchain technologies could be impactful to consumers facing use cases within retail services. Whether to facilitate rewards programs and/or to track compliance with regulations, having a decentralized system of accounting that leverages such properties as tokenization and automation and that allows for issuance, tracking, and reporting of digitized credits and certificates could be very impactful to the resilience and reliability of the future electric grid systems.

In many ways, a decentralized blockchain-based system that serves as the backbone for future retail services directly aligns with future trends for the electric grid as a whole. The grid is becoming increasingly distributed, with bidirectional energy flows from solar photovoltaics (PV), wind resources, and increasingly variable load demand.

2.2. Financial Services

Like DOE, other energy stakeholders are keeping a watchful eye on technology trends that will undoubtedly impact the reliability and resilience of the grid, including but not limited to increased penetrations of variable renewable energy sources, the coming electrification of the auto industry, energy storage, and the increasing flexibility of traditional energy generating units. It is also becoming increasingly apparent that the energy demand due to mining-based cryptocurrencies (e.g., Bitcoin) will also prove to be important in the coming years.

Taking the Bitcoin blockchain and Proof-of-Work (PoW) consensus mechanism as an example, the process of mining new Bitcoin by the near-continuous, competitive calculation of hash functions that satisfy a given mining difficulty is computationally expensive and requires specialized mining equipment that uses a high amount of energy. The energy consumption associated with Bitcoin mining is directly tied to the hash rate, which has been ever-increasing since Bitcoin's inception in 2009. As of 1 June 2022, the current hash rate is 220.2 EHash/s, as shown in Figure 2 [28].

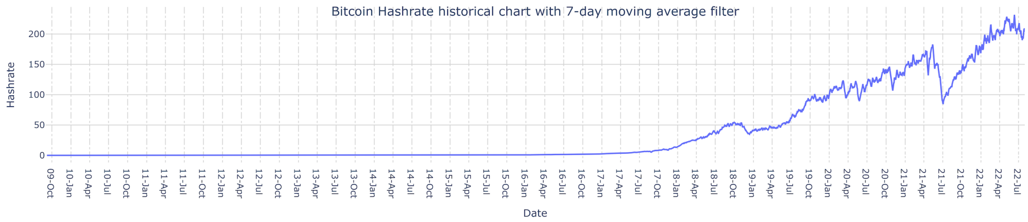

Figure 2. Bitcoin hash rate historical chart (as of 1 June 2022) [28].

As the hash rate has increased over time, the amount of processing power to support the network has also increased. The current state of the art for Bitcoin mining is to use application-specific integrated circuits (ASICs); however, information concerning the specific mining equipment that is used, respective hardware efficiencies, exact geographic locations (which can influence the extent to which an additional balance of plant is needed to support cooling for mining systems), etc., are all questions for those seeking to assess the true energy demand from these cryptocurrency mining systems as a sector.

Because energy consumption information is unknown, reasonable estimates based on simplifying assumptions are all that can be relied upon as a basis for assessment. Methods used to estimate the amount of energy consumption on the Bitcoin network are still being debated, with academic research groups and other organizations putting forth their own methodologies [29–31]. Researchers at the University of Cambridge conducted a Global Cryptoasset Benchmarking Study that provides a comprehensive assessment and insights for digital mining operations around the world [31]. An opportunity for DOE would be to conduct a similar analysis focused on the United States, or, at a minimum, to convene a study that compiles energy consumption estimation methods such that systematic impact analysis can be performed.

In addition to the energy consumed, and to the extent that information can be deduced, a geographic analysis of the types of energy sources (e.g., solar PV, hydropower, geothermal, fossil-based) is also necessary because this impacts the amount of greenhouse gas emissions associated with cryptocurrency mining operations. Additionally, it would be important to understand the trends and cycles on various timescales. Peak usage in various times of the year, weekly, or daily consumption may impact overall peak demands. Conversely, opportunities may exist to balance demand from other usages to help levelized power consumption. This uncertainty about the exact energy consumption and associated emissions for Bitcoin mining poses an issue for the power industry and for policymakers who need reliable information to make informed decisions regarding resource allocation, to assess progress toward decarbonization, and for other developments that will inevitably shape our collective energy future.

2.3. DERs and Renewable Energy

Some DOE-funded research efforts seek to facilitate the coordination of DERs as a part of a transactive energy system. DERs refer to a wide range of energy resources, including wind, solar PV, EVs, battery storage, and fuel cells. Transactive energy systems seek to optimize the coordination and control of DERs through a peer-to-peer, transaction-based marketplace.

There is a need within the DER sector to create a new market interface that orchestrates the exchange of energy resources among disparate systems with multiple parties [32]. In these transactive energy systems for DERs, the inherent properties of immutability and decentralization and/or disintermediation represent the primary features of blockchain that are best suited to be leveraged as a solution for this type of application. Within an active DER ecosystem, multiple entities—including prosumers, DER aggregators, transmission system operators, distribution system operators, etc.—would participate directly in the marketplace, without the use of intermediaries. The decentralization and/or disintermediation property of blockchain can be exploited to facilitate the secure exchange of information (i.e., bids and settlements) among numerous participants in a trustless environment while also maintaining a transparent, immutable ledger that serves as an auditable, shared history of transactions.

DOE researchers in [33] demonstrated the use of blockchain for various stages of DER marketplace transactions (double auction market), including registration/qualification of transactive agents that will participate in the energy system, negotiation between transactive agents and the system coordinator, operation, measurement/verification, and settlement/reconciliation. Similar efforts were conducted by researchers in [34,35], with the former applying blockchain technologies to coordinate energy produced by solar PV systems and the latter demonstrating peer-to-peer energy transactions between two test homes. Research activities within this domain for the electric power industry have also investigated transactive energy systems for DER applications; however, there is an emphasis on green certificate trading, emissions credits, and wholesale energy trading.

Ameren Corporation has partnered with Opus One Solutions on a blockchain-based transactive energy marketplace demonstration effort that leverages Ameren's microgrid in Champaign, Illinois [36–39]. In this project, DERs—such as solar, behind-the-meter batteries, and EVs—will be tested to make decisions autonomously to participate in certain markets or offer grid services. Initial efforts will include modeling the interactions of DERs at one of Ameren's microgrids at the University of Illinois at Urbana-Champaign. This microgrid includes 1 MW of natural gas generation, 500 kWh of battery storage, 125 kW of solar PV capacity, and a 100l-kW wind turbine [39]. The project will then conduct testing of the microgrid systems and controls through a simulated market that will feature day-ahead and real-time prices for energy at the microgrid [37]. In this project, which is still under development, blockchain is being used to track and identification data among multiple devices [37].

Another pilot demonstration project centered on transactive energy systems includes a partnership between Green Mountain Power (GMP) and LO3 Energy to develop an online marketplace to allow customers' businesses in Vermont to buy and sell renewable power. Participants will trade local renewable energy credits (RECs), which the utility is calling "Vermont Green Attributes". GMP established a local energy marketplace for customers via the Vermont Green application Pando from LO3 Energy will enable bidding auctions and connect local energy sellers and buyers. Blockchain will also allow for transparency in transactions, an auditable transaction trail, and a method to verify that the credits are accurate [40,41].

In addition to transactive energy systems, the electric power industry is investigating blockchain technologies to support green certificate trading and emissions credits. Multiple utility-sponsored efforts have been identified in this technical area.

Power Ledger and Clearway Energy Group are working together to develop a REC platform in the United States using Power Ledger's TraceX platform [42]. RECs can represent proof of how much renewable energy is provided per state each year. RECs will be tracked on the blockchain from creation, to transfer and sale, to retirement. This platform will provide an audit trail for RECs by logging transactions, and it prevent the double claiming of REC's in the marketplace. Power Ledger's TraceX platform is a digital marketplace for trading and settlement. This platform can connect to existing REC registries or to use Power Ledger's own Trace registry feature [43].

Energy Web Foundation (EWF) and PJM Environmental Information Services (PJM-EIS) are piloting EWF's EW Origin tool kit in concert with PJM's Generation Attribute Tracking System (GATS). GATS tracks electricity production by generating renewable energy certificates for each megawatt-hour produced by a generator. The current GATS process uses a bulletin board where REC owners can advertise credits, check for purchase requests, work with a third party to purchase REC [44]. EW Origin is a publicly available tool kit built on the Energy Web Chain blockchain. EW Origin is "a reference application showing the transformative power of blockchain in renewable energy certificate and carbon accounting markets" [45]. Each asset can receive a digital identity that links all production of that asset and ownership of the credit. Smart contracts can allow for automated mapping or purchasing based on the consumption profile [45].

NV Energy has partnered with EWF and Sparks to conduct a blockchain-based pilot program where independent renewable energy producers can sell their energy to utilities in exchange for portfolio energy credits (PECs) [46]. In this project, the blockchain used is Energy Web Chain, and the technology would be integrated into a smart meter that logs the energy generated, confirms the provenance of the data, and also issues an equivalent PEC. This project was initiated after the Nevada Public Utilities Commission opened a docket to explore blockchain-based technology to track and certify PECs to determine compliance with renewable portfolio standards. Through this effort, the entire life cycle of PECs—from registration, to ownership, to certification, to tracking, to sale transfer, to retirement—will be observed [46].

Last, the wholesale energy trading concerning *Wholesale Energy Trading* use case, there is one effort that has been identified that Direct Energy is conducting on LO3's Exergy platform for micro-energy hedging. This pilot project offers commercial and industrial customers the opportunity to design and submit orders for energy hedges at the hourly level. Exergy uses "permission tokens" to secure each piece of data based on the owner's requirements. These data, once set to the owner's requirements, can be shared in real time. This will allow participants to predict hourly power needs. This process is somewhat inefficient, and data are not available in real time. This pilot is targeting five commercial and industrial customers. Using blockchain, this pilot hopes to enable commercial and industrial customers to automatically place power hedges at shorter time frames, to identify different sources of energy, and to be matched with the most competitive offer [47].

The large amount of DOE-funded research activities within transactive energy management use case applications show the promise of blockchain technologies to increase efficiency, to integrate operations, and to increase trust in securing transactions between distributed entities. In particular, several projects are exploring applying blockchain technologies for peer-to-peer energy exchanges and marketplace creation for DERs, including solar generation sources. This energy system domain includes projects leveraging each blockchain property, but the largest volume of effort leverages the decentralization and disintermediation property. Given the nature of transactive energy being distributed and the potential for direct transactions, this property might enable more equitable marketplaces with customer participation.

The DOE and utility-led demonstrations for transactive energy systems highlight the natural progression of technology development, with the lower-technical readiness level (TRL) research seeking to prove feasibility. The utility-led demonstrations progress the technology to higher TRL by integrating it into existing microgrids and customer installations. Similar peer-to-peer trading and prosumer marketplaces are then proven in real-world scenarios. In this regard, for this energy system domain, the DOE and utility-led research complement each other in validating blockchain for this common need.

Whereas most DOE-funded research focuses on enabling transactive energy systems, the industry efforts expand the use case applications to include attributing, tracking, and trading renewable energy from independent prosumers. This expansion includes credit-based applications, such as green energy certificates, wholesale energy trading, and RECs.

This additional research focus shows an industry exploration of blockchain properties for tokenization and decentralizing marketplaces for direct peer-to-peer exchanges of these tokenized commodities. This divergence of research focus shows the industry's recognition of the changing roles in an evolving architecture for marketplaces.

As these research projects validate and filter the appropriate applications for blockchain technologies, and there is a need to continue to move the applications toward higher-TRL projects. This would greatly benefit from the diverse expertise in industry (utilities, vendors, small business), laboratories, and academia. In particular, this application domain will evolve to perform exchanges and marketplaces autonomously, enabled by optimized smart contracts. Research explorations can further these proven demonstrations into easy-to-deploy, maintain, and use processes that enable full automation. The final hurdles to the full deployment of new exchange platforms might require demonstrations to identify further approaches for trusting the proper handling of stakeholder data for privacy and anonymity.

2.4. Controls

The use cases for grid automation, coordination, and control are centered around sensor integration, grid communication networks, and data acquisition from grid assets, including EVs and smart buildings. In modern grid systems, the interconnectivity among assets and sensor systems are increasingly complex as the networks become larger and more distributed. With traditional and centralized architectures, the existing energy delivery system and distributed management system for the electric grid is vulnerable to cyberattacks. Data transactions and control signaling among devices, both inside and outside networks, are loosely integrated. Resulting control actions, whether automated or by human response, entirely rely on the integrity of state measurements and data exchanges to/from grid assets. Data tampering and manipulation can adversely affect the resilience and reliability of grid services in terms of network load forecasting, market plan and pricing, and stability analysis; therefore, improving the trustworthiness and security in the data flow of grid information is paramount in this energy system domain.

From the literature review of ongoing and past projects supported by DOE, blockchain has been demonstrated to be a great potential solution to address the shortcomings relevant to the integrity and authentication of the data exchanged for control at the communication layer. As described in the study in [48], the use of a hash calendar-based blockchain has enabled autonomous verification of utility data exchanges from the control data center to multiple entities in remote applications. In this study, the use of a hash calendar was combined with signature tokenization to prove the ability of blockchain to securely protect data flow over broad, untrustworthy networks from tampering, spoofing, and other malicious data modifications. Within the proposed categorization matrix (which will be discussed in Section 4), this was the only activity that had tokenization and immutability as high-priority requirements.

To enhance data integrity and resilience against cyberattacks for data exchanged among DERs, the study in [49] primarily emphasized the deployment of smart contract-based blockchain technologies. The goal was to increase the speed, scale, efficiency, and security of distributed DER and EV transactions, removing interactions with third parties as intermediaries in the exchange. The blockchain execution through smart contracts managed secure transactions and levelled the exchange of excess load generation from DERs, EVs, and business activities through decentralized storage in the ledger.

In addition, DOE-funded research has explored practical ways that blockchain could be leveraged to coordinate and manage sensor networks by logging process signal data and confirming the identity of energy delivery systems equipment and other grid assets. These objectives were achieved by integrating smart sensors and IoT components that could act as nodes in the distributed blockchain architecture, as highlighted in [50–52]. Theoretically, this decentralized blockchain structure ensured better facilitation of peer-to-peer control communications and removed centralized, intermediary systems that are prone to cyber threats; therefore, the integrity and authenticity of the sensor measurements could be preserved for subsequent automated process control actions.

The laboratory-scale demonstrations conducted by DOE can be classified as early-stage R&D, seeking to confirm proof of concept and overall feasibility. Within industry, higher-TRL, pilot-scale demonstrations are being conducted within the same energy domain of grid automation, coordination, and control.

Commonwealth Edison (ComEd) has partnered with Xage Security to investigate blockchain to aid in the coordination and control of microgrid systems [53,54]. The project will focus on simulated tests representing two of ComEd's microgrids: the Bronzeville neighborhood in Chicago, IL, and the Illinois Institute of Technology [54]. The project seeks to leverage blockchain to securely manage bidirectional energy flows throughout energy systems that include power generated from utilities in concert with DERs, such as energy storage and solar. Initial efforts center on using blockchain to verify participants on the network in an access-controlled manner, which thus enables secure transactions and energy exchanges [54].

Another utility/vendor partnership that seeks to leverage blockchain technologies for coordination is Burlington Electric Department (BED) and Omega Grid. This pilot project operates a local energy market platform that considers existing wholesale markets and local grid constraints to effectively manage demand response and determine the most efficient mix of generation and load to manage the distribution grid [55]. The goal is to reduce the peak charges faced by BED. Omega Grid looks to provide a demand response platform capable of engaging with devices as small as smart switches by digitally onboarding, engaging, and delivering rewards to consumers or devices. BED customers will opt into the program and receive tokens in exchange for reducing electricity at designated peak times. Credit for reducing usage will be issued the next day by Omega Grid, which is then settled with BED the following billing cycle. The plan is for tokens to be used with local merchants in the community. Using smart contracts, the participant acknowledges the price at which they are willing to adjust their energy usage. This is their "bid". Customers can elect to receive all notifications for adjusting usage by setting no bid. Omega Grid contacts participants the day before a foreseen peak event. Omega Grid estimates normal customer electricity usage during peak events—this is the estimated baseline. Customers are notified of the expected value, which is the compensation/hour that is expected when the usage is reduced. Compensation is the difference between the estimated baseline, minus the actual usage (meter data), multiplied by the expected value (or compensation/h) [55].

Among the energy system domains for blockchain research, this domain represented the largest identified number of projects and publications from the DOE research. Additionally, with the identified industry pilot demonstrations, there is momentum to increase the TRL for blockchain to lend security properties to coordination and control applications. This shows a broad recognition of the need to increase trust in the integrity of data and communications, including across untrustworthy networks, and to incentivize integration for shared coordination among independent stakeholders. The current research projects are exploring increasing trust in the technology through ledger immutability and managing identities (e.g., metadata) of participating assets in distributed operations.

Although some efforts are underway, the opportunity exists to expand research in the important areas of coordination and control for EVs and smart buildings. As adoption increases, the demand imposed on the grid intensifies, yet modern technologies within these applications enable the opportunity to communicate directly and optimize the ability to satisfy energy needs without risking grid stability. Blockchain could lend efficiency in transactions between stakeholders and increase trust in allowing decentralized automation to reliably coordinate production and consumption at optimal times and locations.

With current research projects focused on demonstrating the utilization of immutability to increase security within applications, there will be a need to focus the final TRL research on overcoming industry barriers to adoption. In this energy domain, numerous independent stakeholders are required to integrate and share information within the community. The research focused on the *Privacy and/or Anonymity* blockchain properties can remove that barrier where concerns such as private information and intellectual property would prevent participation. Finally, to fully realize its potential, focused research on the automation of an application could provide trust in the final TRL achieved and the readiness for market deployment. In this manner, the blockchain application would advance toward production quality, and it would increase a demonstration application's usability and reliability to be ready to deploy.

2.5. Supply Chain Management

Blockchain has been used to improve supply chain management to provide immutable archive records of any assets available in bulk electric system operations [56]. Blockchain was leveraged to address supply chain risk assessments for industrial control system components including networking services to comply with the North American Electric Reliability Corporation (NERC) Critical Infrastructure Protection (CIP) standards [56].

Currently, supply chain records are difficult to efficiently handle because the number of devices and their service networks are substantially increasing. With cryptographic DLTs through PoA consensus mechanisms, blockchain could increase transparency and accessibility to the supply chain data, which would enable greater visibility for utilities to monitor the integrity of their assets and to protect metadata from manipulation and compromise from intermediaries and cyber threats [56]. Immutability was the high valued blockchain property in supply chain asset management. The DOE project leverages blockchain's immutability and disintermediation for authenticating equipment in a more cyber-resilient manner supporting safeguards and export controls of nuclear [57].

Unlike other research efforts that have focused on immutability as the highest-ranked blockchain property, in [58], privacy was a critical feature in the blockchain application. Rather than as a broad application, this study was conducted as a proof of concept of blockchain in retaining manufacturing data in the digital twin process that also linked the physical part to the metadata. The metadata of manufactured components and materials contain the design parameters and information, the printing process, and the post-production analysis. This information is often proprietary to manufacturers and developers, who prefer to limit sharing of this data to maintain a market advantage. In [58] accessibility to the metadata was restricted to the part manufacturers and the subsequent users of the test part via the implementation of QR codes.

The Pacific Northwest National Laboratory performed an R&D scoping study to propose a framework for assessing new technologies and initial opportunities for safeguard system applications to assist the International Atomic Energy Agency (IAEA) to fulfill its obligations [59]. This study proposed common nomenclature and defined deployment models and services to be provided by blockchain. Finally, this framework was demonstrated by mapping the organization's strategic goals and proposing potential application areas in the safeguard system, such as tracking shipments of nuclear materials. The defined deployment models and required services apply to numerous sectors to assess blockchain fit and requirements for an application.

Based on demonstration activities being conducted by the electric power industry, a similar positive outlook has been observed for the use of blockchain to potentially ease life-cycle management. One main use of blockchain is through authentication and validation of products as they travel through the supply chain and during maintenance tasks. A summary of industry activities that were surveyed under the supply chain use case will be discussed during Section 4.

The Global Data Asset Collaborative (GDAC) was launched by VIA, Hawaiian Electric, and Vector to improve predictive maintenance capabilities for transformers [60,61]. In this pilot study, the underlying technology—VIA's Trusted Analytics Chain (TAC)—connects diverse data sets among utilities to perform analytics/benchmarking [54]. Instead of transmitting a copy of the data to an analyst, TAC brings the algorithms that an analyst (third party) wants to run to where the data are located and returns only authorized answers to the analyst [54]. Within GDAC, blockchain is used to store smart contracts that confirm access permissions to off-chain data repositories that store operation-and-maintenance data for transformer equipment throughout its component life cycle [54]. The ability to confirm the identity to provide authorized access to VIA's artificial intelligence-based analytics software while conducting component data sharing in a manner that maintains the privacy of data among multiple parties is a meaningful use of blockchain.

PG&E has also investigated blockchain to support tracking and the chain of custody for assets throughout their life cycle [62]. Known as Smart Asset Management, this project focused on tracking steel reels for wire and cable applications. This fundamental materials tracking via blockchain might provide improved visibility of assets at any point in time and provide an immutable history of the life cycle of an asset (from installation to disposal). Senior executive officials for PG&E also cite the reduction of costs associated with creating and maintaining manual records of asset inventories as well as the chain of custody as an additional benefit to deploying blockchain for this use case application [27,54].

The ability of blockchain to provide device authentication, to confirm the integrity of assets on a network, and to provide an immutable history of the chain of custody are very compelling capabilities that have the resilience. It may aid resiliency of operations as well as post-event forensics after a system is compromised and are recovered. When paired with other technologies, such as advanced pattern recognition and artificial intelligence-based analytics, as in [58], there is an additional opportunity to leverage blockchain for improved observability, monitoring, and confirmation of real-time energy systems operations through device authentication and data integrity.

There was industry sentiment that organizations were more willing to pilot the deployment of blockchain for supply chain use cases because it is not directly tied to power production or load demand and thus represents a relatively lower-risk demonstration [7,63]. The thought is that the supply chains could serve as a proving ground for blockchain to show its utility and to help a traditionally conservative industry acclimate to the technology itself. It is hoped that successful demonstrations will then build confidence and familiarity toward blockchain technologies overall and thus open the door to demonstrations for more complex, disruptive (that pose a higher risk) use cases in the future.

Blockchain may also provide greater granularity for tracking supply chain lifecycle parameters. The supply chain lifecycle in power systems is complex and ranges from initial software development to integration with controls systems providers integration, to deployment, to operations, and finally decommissioning. Operationally, changes to configuration and setpoints may impact reliability of the systems. Understanding and tracking these changes within an immutable ledger can aid operators and security personnel evaluate during troubleshooting and recovery.

There is an opportunity for DOE to support higher-TRL demonstrations of blockchain for supply chain use cases in a manner that seeks to achieve greater DOE mission goals of a secure supply chain infrastructure that also explores novel solutions represented by blockchain technologies [64]. There are extensions of current research that have yet to be significantly explored by either DOE or industry in the form of an integrated approach to the deployment of blockchain and supply chains that investigate the impact of the asset on energy systems operations. Even a relatively straightforward use of blockchain to store metadata that confirms equipment status could be linked to energy systems controls such that the direct impact analysis of that device coming offline for any reason (i.e., vulnerability detected, maintenance required, end-of-life disposal) could be studied. In-depth risk analysis of supply chains to energy systems operations could be performed in a more automated fashion using blockchain technologies.

2.6. Foundational Blockchain Research

Within current DOE-funded blockchain R&D efforts, a wide variety of activities are use case agnostic and advance foundational approaches to be leveraged by domain-specific applications. Examples include fundamental blockchain R&D (e.g., new consensus methods); a fundamental framework that explores ways in which blockchain could be used in the future; network, storage, and compute services; as well as policy and regulations.

The breadth of activities within the foundational research domain speaks to the utility of blockchain technologies in support of virtually any use case as well as the early stage of research for how to create cross-cutting services for energy applications.

In [65,66], blockchain technologies are introduced to increase security, integrity, and trust among users in cloud operations. In [66], a data provenance architecture with a Proof-of-Stake (PoS) consensus model is developed and evaluated as an extendible solution to ensure the legitimacy of data operations. The researchers expanded their study to show that blockchain could be used to establish a data provenance framework for digital objects in the cloud computing [65]. Known as BlockCloud, the platform architecture leverages blockchain's transaction validation and immutability features to track and record data objects associated with cloud environments. This enhanced tracking of cloud-based data operations using blockchain allows for the confirmation of data integrity and the ability to detect and alert users to anomalies.

Oak Ridge National Laboratory conducted R&D scoping studies that explored the promise of blockchain technologies from both an organizational perspective (partnerships, pilot projects, facility resources, etc.) and a hardware-based approach to securing edge-deployed sensor systems [67,68]. In the case of the sensor system in [68], the researchers sought to leverage the immutability and decentralization features of DLTs to verify the integrity of control data and to remove a single point of failure through distributed data sets.

The use of decentralized, distributed information as a method to enhance the resilience of data sets is a major theme for a data storage use case [69–71]. This, in addition to the necessity of data provenance and having an immutable history of data transactions, is a key element for a successful data storage system overall. In [70,71], the metadata related to the file locations or the data transactions are stored on the blockchain. In [70], the actual files are stored off-chain using a distributed hash table, whereas in [71], trust in the data stored in a relational database is increased by immutably recording the off-chain database transactions.

Data integrity assurance for underlying data sets that support a given use case application is extremely important. One example is found in [69], which used blockchain to confirm the integrity of both raw and derived data associated with high-performance computing applications. Researchers were able to leverage the data provenance to identify compromised information by unauthorized tasks and/or computational workloads from a compromised node. If the system is compromised in some manner, the immutability of the ledger allows for post-event forensic analysis to identify which data sets were compromised.

The authors of [72] present a vulnerability assessment framework that has crosscutting applicability to maturing blockchain solutions in all application domains. A Cybersecurity Vulnerability Mitigation Framework through Empirical Paradigm (CyFEr) is proposed to prioritize the requirements of a solution to obtain a desired cybersecurity maturity level. This study evaluated rank weight methodologies for multi-criteria decision analysis applied to a Blockchain Cybersecurity Framework (BC2F) for evaluating the cybersecurity posture of blockchain nodes and networks. Using prioritization approaches and vulnerability assessment tools, such as CyFEr, early and throughout the design life cycle will increase the cybersecurity posture of the network itself and improve trust in the ability of the network to meet the needs of applications.

An integral part of blockchain technologies development and maturation is testing and evaluation. As with any technology, there needs to be a quantitative assessment of performance compared to the current state of the art that it is seeking to enhance and/or displace altogether. For blockchain technology applied to a given use case scenario, a comprehensive performance evaluation is conducted on the blockchain parameters (e.g., transactions per second, transaction capacity, the energy consumption of the consensus mechanism, latency) and also the performance parameters associated with the blockchain-based concept deployed within the context of the use case itself. The researchers in [73] created a DLT-agnostic framework known as Proteus to perform testing on DLT systems using emulation capabilities. Using their FIREWHEEL tool, performance data including (but not limited to) network traffic, disk utilization, and memory.

The BLOSEM project team has built a testing capability known as the BLOSEM Unified Testing Platform (UTP) [63,74]. The UTP leverages DOE laboratory resources in the form of energy systems hardware (gas turbine, sensors, microcontrollers, etc.), software, data distribution platforms (VOLTTRON), and co-simulation environments (e.g., the Hierarchical Engine for Large-scale Infrastructure Co-Simulation HELICS) to enable the testing of a variety of real-world use case applications. Through the UTP, blockchain-based concepts can be evaluated on blockchain performance as well as benchmarking of the deployed blockchain-based concept within a respective use case. These DOE efforts will allow for the independent testing of blockchain concepts at the system and use case level, respectively. It is hoped that through real-world testing and evaluation, viable concepts are accelerated and successfully transitioned to industry [74].

Within foundational research, there are few to no public-facing, industry-led demonstration activities. The only active projects include federally funded efforts sponsored by DOE. This is appropriate and expected because foundational blockchain research is predominantly early stage and low TRL. In addition, these foundational efforts are generally use case agnostic, meaning that the research has broad applicability to multiple use cases. From an industry perspective, decisions about investments in technology innovations such as blockchain need to be tied to a specific use case application such that a business case can be made regarding a possible return on investment (ROI). This is usually centered around high-TRL technologies ready to be implemented in the field; therefore, it is befitting that most activities in this domain be conducted with support from DOE because it is part of the inherent government role to invest in and mature disruptive technologies that represent tangible solutions to industry challenges yet are independent of the immediate ROI.

If funding from the private sector is used to support foundational blockchain research, then the research outcomes are usually proprietary and unavailable to the public; emphasizing the need for publicly funded research at higher TRL testing/demonstration levels. This will aid in the technology transition from research laboratory to industry from a sector-wide perspective as opposed to aiding only one privately funded organization. An additional, collective benefit of having research outcomes from high-TRL demonstrations being publicly available is the steady contribution of knowledge regarding blockchain technologies to the open domain, continually advancing the current state of the art. The by-product of public-facing research outcomes will help accelerate technology development, awareness, and ultimate adoption by industry.

3. Development of Blockchain Use Case Categorization Framework

The goal of this study was to develop a categorization framework that can systematically group blockchain R&D activities based on energy system domains, use case applications, and blockchain properties. Thus, detailed characterization of the existing blockchain activities was required to identify the most representative blockchain use case applications and properties.

3.1. Evaluation of Promising Use Cases

As the first step, a basic grouping of potential blockchain applications was conducted, as summarized in Table 1. In this grouping, similar use cases from existing publications were organized horizontally to provide some insights into the overlapping energy system domain of interest.

The use cases identified by Andoni et al. and shown in Table 1 seemed to be organized around main system-level perspectives, such as *Grid Management* [4]. This category could consider any specific use cases related to the electric grid umbrella, including (1) *DER Coordination*, (2) *Grid Services/Ancillary Services*, and (3) *Transactive Systems and Demand demand management* that were listed by Gourisetti et al. [72]. Additionally, *Flexibility Management* and *Grid Management and Operations*, determined by Stekli and Cali, could also be categorized within grid management [75].

The applicability of multidimensional frameworks for grid operations was also assessed to represent the energy system domains for the categorization technique—for example, the Smart Grid Architecture Model (SGAM) and the National Institute of Standards and Technology (NIST) Smart Grid Interoperability Framework [76,77]. The NIST Smart Grid Conceptual Model presents domain definitions and their interoperability points, and it describes the roles/responsibilities for actors and equipment within domains for the electric grid. Similarly, the SGAM defines a multidimensional model of business domains, architecture zones, and stacked interoperability layers for mapping systems and standards.

Adopting the NIST model domains might have the added benefit of categorizing the role or user of the blockchain applications; however, it would be more difficult to easily express a project focused on crosscutting applications with transactions in each model's domains. Additionally, a role-focused categorization would not be able to express coverage and the research needs for foundational blockchain technologies where all roles and all applications would use the technology. In the context of assessing a blockchain research portfolio, when appropriate, these two conceptual models support complementary additional dimensions for categorization to identify needed opportunities. Projects can be assessed for represented roles to clarify the role that is the focus of a blockchain application or to assess the applicable SGAM interoperability layer to enable specific transactions between NIST domains.

As an example, a research project for a billing application might be categorized within retail services with a focus on transaction immutability. Because billing is relevant to multiple domains in both grid conceptual models, a complementary assessment could clarify that the project intent is to automate information-layer interoperability (e.g., SGAM layers) between roles/services in both the customer and the service provider domains (e.g., NIST domains). This could be used to identify gaps, such as securing the SGAM communication layer to support the meter reading service in the operations domain (NIST). Generally, these frameworks have been adopted in interoperability assessments of smart grid operations for cybersecurity, energy value, and economics [75,78].

Table 1. Existing use case categorization: Each column presents the list of use cases from different references. Each row captures the overlapping nature of the blockchain use case applications across the references (these overlaps are shown using stripped gray bars).

Andoni et al. [4]	**PNNL, Gourisetti et al. [72]**	**Stekli and Cali [75]**	**EPRI [7,79]**	**IBM [63]**
•Metering, billing, and security	•Billing services		•Retail billing •Smart metering—Clearing and settlement	
	•Auditing •Policy and regulations compliance			
	•REC/decarbonization (Smart grid)			•Certifications
•Electric e-mobility	•EV charging	•EV charging/payment settlement	•EV charging	•EV charging
•Cryptocurrencies, tokens, investment		•Energy financing: STO, ICO, and digital equity crowdfunding	•Energy financing	•Energy coins
		•Wholesale trading	•Wholesale energy trading	
	•Market settlements			•Settlement
•Green certificates carbon trading	•REC/decarbonization	•Renewable energy certificates (REC) trading	•Renewable energy credits/carbon trading	
•Decentralized energy trading	•Peer-to-peer market	•P2P energy trading •Retail trading	•Peer-to-peer energy trading	- P2P
	•DER coordination		•DER integration	•DER
•Grid management	•Grid services/ancillary services	•Flexibility management	•Grid flexibility	•Ancillary services
	•Transactive systems and demand management	•Grid management and operations	•Microgrid management •Distribution management	
			•Demand response	•Supply and demand
•IoT, smart devices, automation, asset management	•Smart sensor/decentralized autonomous decision making		•IIoT/IoT device coordination	•Smart meter data
•Electric e-mobility	•Smart automobile (vehicle-to-vehicle)			
	•Grid cybersecurity •Autonomous cybersecurity		•Cybersecurity—Network monitoring and security	•Grid cybersecurity
	•Secure autonomous data acquisition			
	•Asset management		•Asset management, operations and maintenance	•Asset management
	•Supply chain	•Labelling and energy provenance	•Material traceability	•Asset lifecycle
	•Device management			•Decommissioning •Switching suppliers
	•Device integrity	•Cyber security—IIoT/IoT device authentication •Supply chain—Authenticity •DER—Authentication		
	•Configuration, software and patch management IoT patch management		•Cybersecurity—Patch management	
	•Software and hardware license validation			
•General purpose initiatives and consortia				

Meanwhile, to capture the most relevant use cases across the energy and utility industry for EPRI's blockchain demonstration database, EPRI surveyed utility members and performed a literature review of publicly available thought leadership and research pieces [7,79]. These combined efforts led to the categorization of use cases for utility blockchain pilots being tracked [7]. Although there were many blockchain applications and use cases in the utility industry, the practicality and potential of these applications are still being proven. As new use cases are identified or disproven, it is expected that the use categorization list established by EPRI will grow or shrink.

In summary, categorization techniques for blockchain use cases within the energy system domain could vary, depending on the levels of the information assessment. To extract meaningful and essential context from the developed categorization framework, the principles behind the selection of the viewpoint dimension needs to be clear—whether the intent is to deliver a sufficiently high system-level evaluation or to include more specific blockchain functionality details.

So, a 2-D categorization method for blockchain use cases was developed in this work to address both the energy system domain-based categorization and the functional-level categorization. The focus of the functional-level categorization was around the blockchain properties only. For simplicity, neither the type of data transactions nor the grid blockchain segmentation was considered for the proposed categorization method. Our goal was to have a simple and general classification framework that is extensible to map any blockchain activities to their energy application while also being able to identify the properties of the blockchain technology being leveraged by the projects.

3.2. Two-Dimensional Blockchain Use Case Categorization Framework

Promising use case applications for blockchain deployment in the energy sector were chosen based on the assessment of blockchain use case categories in the previous section. Experience and insights from blockchain experts from DOE laboratories and utility industry partners were leveraged to help identify compelling blockchain use cases [63].

3.2.1. Categorization of Energy System Domains

The 2-D categorization methodology proposed in this work establishes *Energy System Domains* as the first ordinate dimension. As shown in Figure 3, six *Energy System Domains* were identified to represent 30 use case applications within the energy sector that were down-selected as the most compelling cases. Their applicability to each domain was provided based on the definitions established within this article.

These use cases varied across different R&D levels, technologies, and operational implementations. Although the mapping methodology aligned with past and ongoing projects, the foundational structure and categorization framework can be extended to include any additional and new use cases for future blockchain applications.

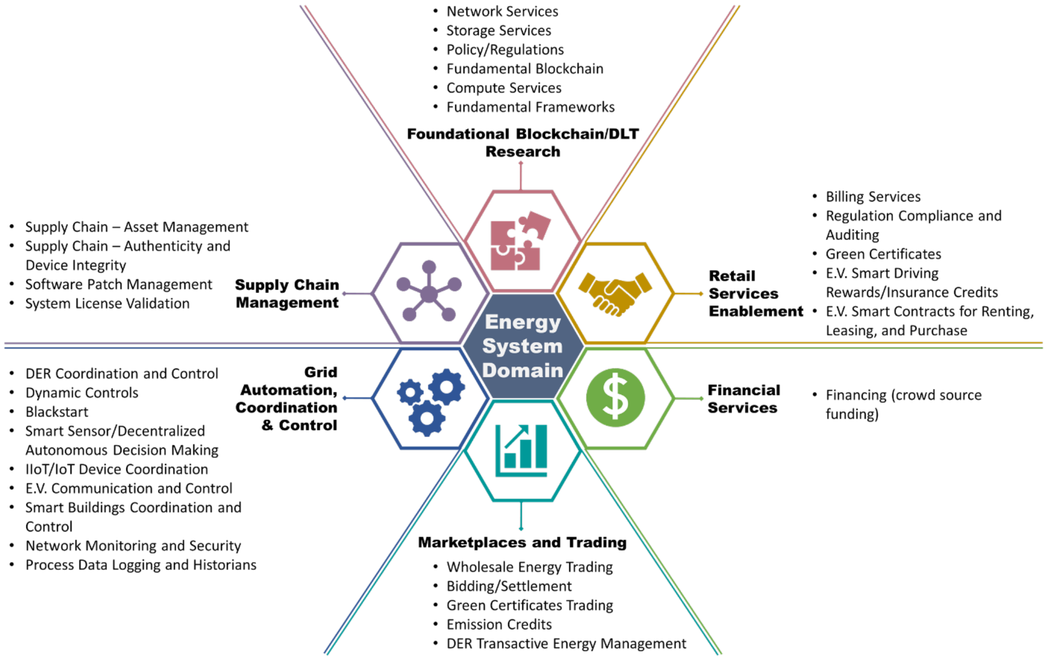

Figure 3. Blockchain energy system domains and use case categorization.

Retail Services Enablement

The main attribute of *Retail Services Enablement* is the transactions and activities that streamline consumer-facing services. Blockchain technologies can be used for billing agreements and payments, metering, and confirming the traceability of energy production and consumption. In addition, this domain encompasses items such as audits, regulation compliance, and promotional rewards, such as renewable energy certificate issuance or smart driving rewards for EVs. Other relevant activities could be EV renting, leasing, and purchasing. One common trait for these activities is the progression around tokenization as the main digital mechanism in the distributed transactions.

Financial Services

The exchange of tokenized assets for financial transactions, such as cryptocurrency, is determined to be the unique feature of this use case domain. In this category, one of the best examples includes the use of cryptocurrency to raise capital in the form of crowdfunding. Many applications might be able to take advantage of cryptocurrency-based crowdfunding, such as co-ownership of energy systems assets and investment. Other examples include the use of cryptocurrency for low-carbon generation initiatives, where generators receive cryptocurrency-based rewards for their low generation of carbon [4]. The concepts of cryptocurrency are designed with tokenizing assets and subsequently exchanging the tokens for cryptocurrencies. In this manner, this domain complements the other categories that primarily focus on tokenizing assets or energy transactions.

Marketplaces and Trading

The *Marketplaces and Trading* domain focuses on how transactive energy systems can more effectively engage grid assets by communicating the true value of energy services and establishing a market in which to transact the services. Theoretically, blockchain would serve as a transparent platform for energy market participants, enabling direct access to demand and production capacity in the marketplace with new roles and responsibilities that could help to regulate the market prices of energy. This could include any transactions and interactions among several entities in the power generation and energy delivery chain at the generation, transmission, and distribution levels, such as consumers, energy retail suppliers, renewable energy generators, or small-scale energy producers. This classification includes any blockchain project associated with trading and strategies that have emerged for bidding; energy imbalance settlements or energy trading in wholesale markets; and peer-to-peer markets, especially among DERs.

This publication treated green certificates issuance and green certificates trading as two separate use case applications that reside in different energy system domains. The establishment and issuance of the green certificate is a tokenization step that is separate from the act of trading that tokenized certificate in a marketplace setting; therefore, the certificate issuance function maps to the *Retail Services Enablement* domain, whereas the trading portion is considered in the *Marketplaces and Trading* domain. Last, this work proposed a more general *Emissions Credits* use case as opposed to *Carbon Credits* only. This allows for additional types of emissions to be considered, including sulfur dioxide, nitrogen oxides, and volatile organic compounds.

Grid Automation, Coordination, and Control

In this paper, *Smart Sensor/Decentralized Autonomous Decision Making* refers to sensor technologies that are enhanced with some level of compute capability and/or on-node processing that allows for advanced operations beyond basic communications of measurement signals. This can include on-node storage, signal processing, analytics, etc. In our case, *the Smart Sensor/Decentralized Autonomous Decision Making* use case was differentiated from that of *IIoT/IoT Device Coordination*, which refers to all other applications of ubiquitous, connected devices and assets.

Supply Chain Management

The control feature of this domain is the implementation of blockchain in supply chain management, which enables monitoring and tracking of the integrity and provenance of the chain of custody for both hardware and software. This includes software patches, asset licenses for physical assets and software, tracking DER assets and devices, etc. Typically, this category would involve interactions among multiple parties, including customers, vendors or manufacturers, and hardware and software suppliers that might be designed for procurement and manufacturing or operational purposes.

In this work, the supply chain use cases are divided into four applications: (1) *Supply Chain—Asset Management*, (2) *Supply Chain—Authenticity and Device Integrity*, (3) *Software Patch Management*, and (4) *System License Validation*. *Supply Chain—Asset Management* enables streamlining records of asset movement and security throughout the supply chain, such as (but not limited to) installation, maintenance, and decommissioning. This also has applicability to software, hardware, and the supply chain of fuels and raw materials. Meanwhile, *Supply Chain—Authenticity and Device Integrity* is primarily responsible for activities to maintain the product's authenticity and verifying its component integrity. *Software Patch Management* is associated with the verification of authentic vendor software patches, and *System License Validation* is for validating asset licenses for physical assets and software.

Foundational Blockchain Research

Use cases within the *Foundational Blockchain Research* domain have applications across multiple energy system domains. Examples include activities that focus on the network, storage, and compute services as well as fundamental blockchain and frameworks for blockchain evaluation and requirements. Additionally, any blockchain efforts that explore opportunities to leverage blockchain or to develop standards pertaining to blockchain's use in energy systems are also included within this domain. It is expected that the scope of the fundamental blockchain, fundamental frameworks, and the policy and regulations use cases are very broad and blockchain agnostic, in which all blockchain properties are applicable. It is hoped that through the addition of this *Foundational Blockchain Research* domain, the extensibility of the categorization framework is highlighted because it allows for these types of efforts to be identified and assessed as part of the larger portfolio of R&D efforts.

3.2.2. Categorization of Blockchain Properties

The second dimension of the proposed 2-D categorization method includes high-priority blockchain properties. Because most developing blockchain use cases leverage multiple fundamental blockchain properties, this *categorization method assigns each surveyed project to the two primary properties being leveraged by the research project or demonstration*. In this manner, use case research can be further categorized based on the purpose of using the blockchain. Parallel research projects might use blockchain for the same energy application use case; however, they might focus on researching the use of separate properties. For example, two projects might develop technology for trading green certificates but focus on diverging blockchain properties, such as the immutability of the trade transaction and the privacy of the trader information. This information was obtained from each individual blockchain study and project identified in the literature review.

Consistent with application- agnostic use cases *Policy and Regulations*, *Fundamental Blockchain*, and *Fundamental Frameworks* under the *Foundational Blockchain Research* domain, all six blockchain properties listed in Table 2 could be applied. Therefore, these three use cases were excluded from the 2-D framework.

Before mapping the use cases into the categorization matrix, this section presents the definitions of the blockchain properties. Six categories of blockchain properties are identified and summarized in Table 2.

Table 2. Blockchain properties.

Blockchain Property	Description	Benefits
Immutability	Tamper-proof archival records and data. Applications are primary built to support verification, validation, tracking, and/or auditing.	Protecting data from malicious tampering, increasing the transparency and audibility of data and transactions
Identity Management	Ability to record the information of both physical and digital assets in addition to transactions within distributed ledger technologies	Managing identities; access control; authentication; data provenance; recording metadata; and maintaining records of ownership
Asset Digitalization and Tokenization	Enables new financial and incentive-based use cases using crypto tokens, which can represent tangible or intangible assets. The token represents the economic value of the representative asset or a fraction of the representative asset.	Managing financial services; payments; promotional rewards; market auctions; more efficiently recording quantities, trading, and pricing

Table 2. *Cont.*

Blockchain Property	Description	Benefits
Decentralization and/or disintermediation	Enables direct entity-to-entity interactions or peer-to-peer applications, which contributes to distributed administrative authority instead of traditional centralized architectures and enables collaboration within trustless environments	Direct access to blockchain data storage and information; increasing trustworthiness of data; reducing and/or removing reliance on the intermediatory trust; allowing decentralized coordination
Automation	Smart contract-enabled applications can automate transactions, enabling use cases focused on self-governance, automation, and/or autonomy. Autonomous coordination and control is one example that could fall within this category.	Automating process and decision making, increasing efficiency and accelerating operations
Privacy and/or Anonymity	Cryptographic methods, particularly hash functions and digital signatures, make privacy and integrity possible in a trustless environment. Use cases that primarily differentiate themselves on privacy preservation should fall under this category.	Protecting privacy of data, intellectual property, and personally identifiable information of customers; anonymizing to remove unwanted traceability

Immutability

A primary strength of blockchain technologies is the ability to provide a permanent, unalterable history of transactions. In this manner, energy domain applications can increase trust in the integrity of the ledger information and the ability to detect tampering of the information on compromised nodes. This becomes a particularly important incentive for trust in shared transactions between collaborating yet competing stakeholders and in low-trust environments. Immutability enables more efficient methods of auditing, tracking, analytics, and verification of transactions performed within the respective use case application.

Identity Management

Blockchain technologies enable applications looking to solve the numerous challenges of securely managing digital identities in energy applications. The identity property can begin with the access credentials to transact in a blockchain network but goes beyond that to managing singular identities for transacting entities or individual records of information. Proving and recording identities might be required for all types of actors in transactions, such as people, organizations, IoT devices, records, and/or communicating applications.

Blockchain can be leveraged to create systems for global, self-sovereign identifiers that are supplemented with attributes and permissions. Through consensus and immutability, these identifiers and attributes can be trusted as having been attested to by participants on the network at a snapshot in time. Applications may research authenticating transactions with ledger recorded identities, authorizing transactions from stored attributes for an identity, or tracing provenance of transactions for an identity. Finally, this property can also be selected if the research goal is the secure handling of identities via decentralization, sharding, or zero-knowledge proofs.

Asset Digitization and Tokenization

Through cryptography, digital objects, and smart contracts, new digital approaches to uniquely represent, act on, and divide assets are possible in a blockchain network. Tokenized assets can take the form of representing a tangible object (e.g., device, monetary unit) or an intangible asset (e.g., license, fraction of ownership). Tokens can be designed for use as a security token for investments, a utility token to enable usage, or to represent currency for exchanges.

In this manner, this property can be used to represent economic value or a quantity of production, and it can be divisible into fractional ownership to transfer between network participants. But it can also be used to digitally represent unique characteristics about an asset or to allow permissible actions for an asset. The goal of this property for use cases is to enable applications more efficiently such as payments, promotional rewards, markets, auction exchanges, trading, and recording produced/consumed quantities.

Decentralization and/or Disintermediation

One main purpose for the introduction of blockchain technology was to create a distributed network that moves control from a centralized entity and distributes administrative authority for a given application within a community (e.g., decentralization). Additionally, trust in the security of transactions can remove the processing layers between producers and consumers to enable direct peer-to-peer interactions (e.g., disintermediation).

Use cases can look to leverage this property to establish transparency and collaboration amid a consortium of independent and/or administrative stakeholders. This property could be the primary focus for use cases that enforce agreed-upon rules, transparency, and transferring digital operations that traditionally occur through a trusted centralized entity. Additionally, this property lends well to geographically distributed processes that would benefit from decentralizing transactions and increasing trust in transactions executed on closely located decentralized infrastructure.

Automation

Smart contracts provide the ability to securely execute logic in distributed blockchain nodes. This logic represents the rules to automatically enforce when a transaction must occur and what takes place. These smart contracts can enable use cases to automate processes and decision making in energy domain applications.

Trusting automation becomes particularly important in geographically distributed processes and shared operations among participants in low-trust environments. The automation property can be leveraged to build applications for such purposes as autonomous operations, agreement enforcement, transaction verification, and analytics. A community of collaborating stakeholders can use automation, enabled by smart contracts, to jointly define rules that are digitally enforced by the network to create processes for self-governance for more efficient peer-to-peer transactions.

Privacy

It is important for use cases to leverage or add new technologies to a blockchain application to protect privacy and/or anonymity. This can take the form of protecting privacy within the data, such as personally identifiable information of customers or the intellectual property of participating organizations. Additionally, it can be desirable to protect against the traceability of a transaction to an individual or a participating organization.

Privacy and anonymity are not inherently provided as a property of every blockchain network, and they depend on many factors, such as permissioned vs. public ledgers. Some blockchain networks are specifically built to provide the cryptographic approaches that enable these properties, whereas others are fully transparent once an identifier (e.g., wallet address) is associated with a participant. This property can be selected as the primary focus for the research when the primary value proposition of the project is privacy preservation.

4. Analysis of Blockchain Projects in U.S. Energy Sector

In realizing the goal of the categorization framework proposed in this work, an assessment of the existing portfolio of blockchain activities in the United States was performed. Overall, a total of 110 blockchain activities were successfully tracked and mapped in the developed 2-D categorization matrix, as tabulated in Table 3. It is necessary to understand the traits of each blockchain project and the applicability of the intended blockchain attribute during assignment in the 2-D categorization matrix.

The 2-D categorization matrix lists six energy system domains in the first column, followed by associated use cases in the second column, and six categories for the selected priority blockchain properties are horizontally listed at the top of the matrix. A simple color scheme was used to map all the blockchain activities in the categorization matrix to clearly differentiate the pattern of the existing blockchain portfolio between DOE and the U.S. power utilities: All references inside an orange box refer to DOE-sponsored projects, including any R&D activities that were conducted at national laboratories, universities, small companies, or other research institutes; meanwhile, non-boxed references represent the activities conducted within the U.S. electric power industry, which includes pilot demonstrations, beta tests, and other R&D efforts. It was found that all 110 blockchain activities surveyed in this work were well represented by the proposed use case classification and blockchain properties. Details on each of the surveyed use case will be shown in Tables 4–13.

Table 3. The 2-D blockchain categorization matrix, which contains energy system domain with associated use cases and high-priority blockchain properties. Orange boxes indicate DOE-funded projects; unmarked boxes represent projects funded by the U.S. power industry.

Domains/ Categories	**Use Case Applications**	**Immutability:** *Tamperproof Record of Historical Data, e.g., Verification, Auditing, Tracking Applications, Transparency*	**Identity Management:** *Recording Metadata About Physical and Digital Assets, e.g., Voting Applications*	**Asset Digitization, Tokenization:** *Tokens to Represent an Underlying Tangible or Intangible Asset, e.g., Fractional Ownership Applications*	**Decentralization, Disintermediation:** *Direct Entity-to-Entity Interaction, e.g., DeFi*	**Automation:** *Smart Contract Enabled Applications, e.g., Self-Governing Applications, DAOs*	**Privacy, Anonymity:** *Preserving Privacy and Integrity in Trustless Environment, e.g., Medical Records*
Retail Services Enablement	Billing Services						
	Regulation Compliance and Auditing						
	Green Certificates (e.g., renewable energy credits)	**[25,43]** [80]	[80]	**[25,43]**			
	E.V. Smart Driving Rewards/Insurance Credits			[26] [27]		[26] [27]	
	E.V. Smart Contracts for Renting, Leasing and Purchase			**[23–25]** [26]		**[23–25]** [26]	
Financial Services	Financing (e.g.,crowd source funding)			[81]			[81]
Marketplaces and Trading	Wholesale Energy Trading			[47]	[47]		
	Bidding/Settlement (e.g., FERC 2222)						
	Green Certificates Trading	**[25,43]** **[44,45]**		**[25,43]** **[44,45]** [46]		[46]	
	DER Transactive Energy Management (e.g., trading, P2P, etc.)	[33]	[32] [33] [34] [35] [63][82] [83] [84] [85] [86] [87] [88] [89] [90]	**[36–38]** **[40,41]** [87] [91]	[32] [34] [35] **[36–38]** **[40,41]** [63] [82] [83] [84] [86] [88] [89] [92] [93] [94] [95]	[90] [91] [92] [93] [94] [96]	[85] [95] [96]
	Emission Credits (e.g., carbon, NOx, SOx trading, etc.)			[97] [98]	[97] [98]		
Grid Automation, Coordination Control	DER Coordination & Control	[49] [99]	[37] **[53,100]** [55]		[49] [99] [101] [102]	[37] **[53,100]** [55] [101] [102]	
	Dynamic Controls (e.g., control system communication management)	[103] [104]	[104] [105] [106][107]		[105] [106] [107] [108] [109] [110]	[103] [108] [109] [110]	
	Blackstart						
	Smart Sensor/Decentralized Autonomous Decision Making	[50]	[50] [111]		[111]		
	IIoT/IoT Device Coordination	[52] [112]	[52] [112] [113] [114]			[113] [114]	
	E.V. Communication and Control	[115]			[115]		
	Smart Buildings Coordination and Control	[116] [117]	[116] [117] [118]		[118]		
	Network Monitoring and Security (e.g., data collection, data analytics)	[51] [119] [120] **[121,122]**	[119] [120] **[121,122]** [123]		[51] [123]		
	Process Data Logging and Historians	[48] [124] [125] **[126,127]** [128]	[124] [125] [128]	[48]		**[126,127]**	
Supply Chain Management	Supply Chain—Asset Management (e.g., installation, decommissioning, EV battery swapping)	[56] [57] [59] [63] [129] [130] [131] [132] [133] [134] [135] [136] [137] [138]	[56] [57] [58] [59] [60] [63] [129] [130] [131][132] [133] [134] [135] [136] [137] [138]				[58] [60]
	Supply Chain—Authenticity and Device Integrity	[27]	[27] [139]		[139]		
	Software Patch Management		[140]		[140]		
	System License Validation						
Foundational Blockchain/ DLT Research	Network Services	[67] [68]			[67] [68]		
	Storage Services	[71] [141]	[70] [71] [141]		[70] [141]		
	Compute Services (e.g., HPC, applications hosting, etc.)	[65] [69]	[65] [66] [69]		[66]		
	Policy/Regulations	[142]					
	Fundamental Blockchain (e.g., consensus, evaluation, zero-knowledge proofs, etc.)	**[63,74]** [73] [142] [143] [144] [145] [146] [147] [148]					
	Fundamental Frameworks (e.g., cybersecurity, etc.)	[72] [78] [149]					

Notes: Certain works are part of the same funded project and are grouped together to indicate their relationship (using bold, square brackets). For example, citations **[40,41]** are part of the same funded effort. Citation [25], is included in multiple groups due to being a software solution.

Table 4. Blockchain use cases in the Retail Services Enablement domain within DOE.

Use Case Application	Blockchain/DLT Scope	References
Green Certificates	Use of blockchain to mitigate fraud in carbon credits, improve food chain security, monitor and manage sustainability by tracking agricultural input relevant to environmental benefit credits (i.e., bio-stimulant), and assess tangible and intangible environmental benefit credit assets.	[80]

Table 5. Blockchain use cases in the Retail Services Enablement domain within the U.S. utility industry.

Use Case Application	Blockchain/DLT Scope	References
Green Certificates	Development of a REC platform in the United States using Power Ledger's TraceX platform to track RECs will be tracked on the blockchain from creation, transfer and sale, and retirement. This platform will provide an audit trail for RECs. The goal is to prevent the double claiming of RECs in the marketplace.	[25,43]
EV Smart Contracts for Renting, Leasing, and Purchase	Pilot of Power Ledger's TraceX platform to track and measure credits in the Low Carbon Fuel Standard using solar panels and EV charging infrastructure in a multistory parking garage	[23–25]
EV Smart Driving Rewards/ Insurance Credits	Pilot of Omega Grid's local electricity market software to coordinate EV charging with solar generation	[26]
EV Smart Driving Rewards/ Insurance Credits	BMW and PG&E collaborative pilot to incentivize drivers to charge their EV during hours when the grid has ample solar generation.	[27]

Table 6. Blockchain use cases in the Financial Services domain within DOE.

Use Case Application	Blockchain/DLT Scope	References
Financing	Blockchain was developed to enable flexible financial credit agreements for low- and moderate-income participants in solar financing programs by providing a platform for the approval process, energy asset management, and crowdsourcing investments.	[81]

Table 7. Blockchain use cases in the Marketplaces and Trading domain within the perspective of projects sponsored by DOE.

Use Case Application	Blockchain/DLT Scope	References
DER—Transactive Energy Management	Use of BlockCypher to demonstrate a blockchain-based DER marketplace on two test homes	[32]
DER—Transactive Energy Management	Development of a blueprint architecture to use permissioned blockchains for transactive systems and energy markets	[33]
DER—Transactive Energy Management	Blockchain-based energy trading platform for DERs in the distributed solar/PV market	[34]

Table 7. *Cont.*

Use Case Application	Blockchain/DLT Scope	References
DER—Transactive Energy Management	Real-time energy market for DERs enabled by blockchain, with a focus on commodity tracking	[35]
DER—Transactive Energy Management	Implementation of blockchain with a unified testing platform that includes participation of a DER aggregator in the wholesale electricity markets and visibility of proposed DER operations for the distribution system operator	[63]
DER—Transactive Energy Management	Summary discussion of blockchain and smart contracts to transact DER services in the peer-to-peer marketplace	[82]
DER—Transactive Energy Management	Implementation of a blockchain-based network for peer-to-peer trading of solar energy using Hyperledger	[83]
DER—Transactive Energy Management	Use of an open-source blockchain platform for solar energy exchange	[84]
DER—Transactive Energy Management	Implementing transactive energy markets using blockchain technology to enable zero energy export on the primary feeder by optimizing supply and demand at the distribution level and by optimizing home energy management systems	[85]
DER—Transactive Energy Management	Development of a private, permissioned, and open-source blockchain, called MultiChain, for decentralized peer-to-peer transactive energy trading, with a focus on storage capacity to match intermittent DERs	[86]
DER—Transactive Energy Management	Application of blockchain for a transactive energy service system that provides retail market-clearing mechanisms for peer-to-peer trading of behind-the-meter DERs based on ramping, capacity, and storage prices	[87]
DER—Transactive Energy Management	Use of blockchain-enabled smart contracts to construct a transactive energy platform with predictive optimization for DERs	[88]
DER—Transactive Energy Management	Development of a blockchain-enabled open architecture platform that will allow commercial and industrial buildings to buy and sell excess rooftop PV energy generation and energy consumption reduction in a secure and reliable way	[89]
DER—Transactive Energy Management	Building a Vickrey auction smart contract on EWF's blockchain (Tobala, currently known as Energy Web Chain)	[90]
DER—Transactive Energy Management	A common data infrastructure to integrate heterogenous data sources, including advanced metering infrastructure, generation, and energy transaction data	[91]
DER—Transactive Energy Management	Application of blockchain through an open and extensible co-simulation environment (HELICS) for transactive energy markets, with a focus on a comprehensive assessment of the market designs	[92]
DER—Transactive Energy Management	Development of a blockchain smart contract template for transactive energy system management that ties various personal, legal, and contractual obligations to engineering operations	[93]

Table 7. *Cont.*

Use Case Application	Blockchain/DLT Scope	References
DER—Transactive Energy Management	Implementing blockchain as a *Transaction Management Platform* for an automated auction and matching system that supports the energy trading workflow, prosumer privacy, and operational safety	[96]
DER—Transactive Energy Management	Use of an advanced demand response smart contract integrated with intelligent control for DER operations and dynamic loads through peer-to-peer energy transaction and markets	[94]
DER—Transactive Energy Management	A peer-to-peer energy exchange platform using blockchain technology to enable and manage microservice transactions on the distribution grid	[95]

Table 8. Blockchain-based demonstration projects conducted by the U.S. utility industry within the Marketplaces and Trading domain.

Use Case Application	Blockchain/DLT Scope	References
Wholesale Energy Trading	This pilot offers commercial and industrial customers the opportunity to design and submit orders for energy hedges at the hourly level	[47]
Green Certificate Trading	Development of a REC platform in the United States using Power Ledger's TraceX platform to track RECs on the blockchain from creation, to transfer and sale, to retirement. This platform will provide an audit trail for RECs. The goal is to prevent the double claiming of RECs in the marketplace.	[25,43]
Green Certificate Trading	Piloting EWF's EW Origin tool kit with PJM's GATS. GATS tracks electricity production by generating certificates for each megawatt-hour produced by a generator.	[44,45]
Green Certificate Trading	Initiated after the Nevada Public Utilities Commission opened a docket to explore blockchain-based technology to track and certify PECs to determine compliance with renewable portfolio standards	[46]
DER—Transactive Energy Management	Piloting peer-to-peer energy trading at the Ameren microgrid in Champaign	[36–38]
DER—Transactive Energy Management	This pilot developed a peer-to-peer energy marketplace for business owners and customers in Vermont.	[40,41]
Emissions Credits	Demonstration of a blockchain community to track decarbonization, solar, storage, fast-charging EV stations, and virtual power plants	[97]
Emissions Credits	Grid+ has begun acting as a retail electricity provider in Texas using blockchain technology, enabling cryptocurrency payments with efforts to increase transparency and drive efficiency.	[98]

Table 9. Blockchain use cases in the Grid Automation, Coordination, and Control domain within projects sponsored by DOE.

Use Case Application	Blockchain/DLT Scope	References
DER Coordination and Control	Blockchain-based smart contract applications in energy infrastructure for increased data fidelity, speed, scale, and security of exchanges in DERs	[49]
DER Coordination and Control	Identifying the roles of blockchain in ensuring the improved fault tolerance of grid operations, including communications, physical, weather, and cyber-related faults	[99]
DER Coordination and Control	Use of blockchain-based smart contracts to improve cyber resilience in smart grid applications	[101]
DER Coordination and Control	Developed an optimization algorithm called the distributed consensus-based alternating direction method of multipliers (DC-ADMM) for DERs and battery energy storage systems and applied blockchain to support information exchange and synchronization in distributed optimization solutions associated with DC-ADMM	[102]
Dynamic Controls	Developed a blockchain federated system to control multiregional, large-scale power systems by coordinating local controllers and a multi-artificial intelligence agent system that was designed with distributed deep reinforcement learning to develop a malicious attack-tolerant capability	[103]
Dynamic Controls	Developing a blockchain-based platform to securely and efficiently transmit grid data among sensors, residential devices, and power plants. Potential applications include immutable grid sensor data, real-time blockchain-based grid monitoring and control, and peer-to-peer energy transactions.	[104]
Dynamic Controls	Blockchain application in smart grid protection relay systems to enhance data exchange security with improvement in throughput, scalability, and flexibility for fault detections considering uncertainties	[105]
Dynamic Controls	Developing DSEAL, a blockchain-based system for secure verifications of control command signals and transactions of real-time sensor data in fossil energy-based systems	[106]
Dynamic Controls	Use of blockchain to provide security for legacy and modern grid assets by creating identities and controlling access to assets from multiple vendors. The techniques were used for achieving sensor data source authenticity and integrity across multiple data producers and consumers using DLT regardless of vendor device, network, or industry protocol.	[107]
Dynamic Controls	Cloud-based blockchain to ensure security of industrial controls for energy generation systems	[108]
Dynamic Controls	Assessing the impact of blockchain delay on the dynamic performance of inverter control and communication systems connected to the grid	[109]
Dynamic Controls	Incorporating a consensus mechanism on blockchain technology for a distributed control strategy for alternating current (AC) microgrid control in DER systems	[110]

Table 9. *Cont.*

Use Case Application	Blockchain/DLT Scope	References
Smart Sensor/ Decentralized Autonomous Decision Making	Blockchain was deployed to represent sensor nodes (and vice versa) for identity and authentication, which help route the (sensor) nodes in the network.	[50]
Smart Sensor/ Decentralized Autonomous Decision Making	Developing a peer-to-peer transaction network built on a smart meter-based peer-to-peer transaction network that uses existing, patented hardware, with a focus on providing secure information to the utility about power usage and managing transactions between prosumers and consumers while maintaining the privacy of those identities from other network members	[111]
IIoT/IoT Device Coordination	Deployment of smart inverters with a built-in IoT that could serve as a node device on blockchain for behind-the-meter PV systems	[52]
IIoT/IoT Device Coordination	Building an innovative, proof of concept software platform, called E-Blockchain, to enable secure transaction and control applications that involve the integration of centralized and decentralized power plant control systems with Industrial Internet of Things (IIoT) networks	[112]
IIoT/IoT Device Coordination	A blockchain-based data bus was developed for real-time measurements from smart sensors and IIoT for automated well drilling and completion.	[113]
IIoT/IoT Device Coordination	Developing a novel interaction tool that bridges a robot operating system and blockchain through Ethereum	[114]
EV Communications and Control	Blockchain was proposed for an intra-vehicular communication and control network.	[115]
Smart Buildings Coordination and Control	Evaluation of blockchain applicability to building data applications	[116]
Smart Buildings Coordination and Control	Implementation of a highly scalable blockchain platform, Bassa, for smart city-based applications to realize real-time transactions with concurrent transaction executions	[117]
Smart Buildings Coordination and Control	Blockchain was leveraged to improve wireless sensor networks and the control optimization of intelligent building energy management systems.	[118]
Network Monitoring and Security	Use of blockchain in the decentralization of data communication networks for physical security systems to increase resilience and security prioritization	[51]
Network Monitoring and Security	Integrating a blockchain/peer-to-peer-enhanced cybersecurity protection system into a software-defined networking-enabled cybersecurity protection system to demonstrate cost-effective reinforcement on safeguarding the operations of fossil fuel power generation systems (for detecting compromised controllers in a software-defined network)	[119]
Network Monitoring and Security	Improving the data integrity of field devices and industrial equipment at the source and during data transport using blockchain	[120]
Network Monitoring and Security	Integration of blockchain and a novel networking protocol for the cybersecurity of utility-scale solar energy systems	[121,122]

Table 9. *Cont.*

Use Case Application	Blockchain/DLT Scope	References
Network Monitoring and Security	Integration of a secure blockchain overlay network and model-assisted machine learning for power network security in command and control protocols	[123]
Process Data Logging and Historians	Hash calendar-based blockchain was used to maintain the integrity of a database and secure grid networks for supporting regulatory audits, the market plan, and grid operations and control	[48]
Process Data Logging and Historians	Use of blockchain to enhance cybersecurity for machine-to-machine interactions, infrastructure for secure data logging for sensors, decentralized data storage, and second-layer technologies for high-volume machine-to-machine interactions in fossil fuel power generation systems	[124]
Process Data Logging and Historians	Developing a blockchain-machine learning platform for secure data logging and processing in fossil fuel power generation systems even when the systems are under various cyberattacks, such as false data injection and denial-of-service attacks	[125]
Process Data Logging and Historians	Demonstration of a blockchain architecture and client software to collect and store near-real-time data from a hardware-in-the-loop test bed. Modeled the NASPInet organizational framework for phasor measurement unit data.	[126,127]
Process Data Logging and Historians	Use of blockchain-based smart contracts for building a database system based on the assignment, verification, and registration of unique building identifiers	[128]

Table 10. Blockchain-based demonstration projects conducted by U.S. utilities within the Grid Automation, Coordination, and Control domain.

Use Case Application	Blockchain/DLT Scope	References
DER Coordination and Control	The goal of this project is to test the viability of a transactive energy marketplace.	[37]
DER Coordination and Control	ComEd and Xage Security look to blockchain for potential improvements in operational and security benefits as well as sustainability and resilience goals, such as the integration of DERs with solar, storage, energy efficiency, and demand management.	[53,100]
DER Coordination and Control	This pilot, conducted by Burlington Electric Department and Omega Grid, operates a local energy market platform that considers existing wholesale markets and local grid constraints to effectively manage demand response and determine the most efficient mix of generation and load to manage the distribution grid.	[55]

Table 11. Blockchain use cases in the Supply Chain domain within projects sponsored by DOE.

Use Case Application	Blockchain/DLT Scope	References
Asset Management	Benefits of blockchain in supply chain management of a complex energy infrastructure and NERC CIP compliance	[56]
Asset Management	Use of blockchain in the life-cycle monitoring of uranium hexaflouride (UF6) cylinders to support identification, verification, safeguard, and export control requirements	[57]
Asset Management	Demonstration of blockchain in the manufacturing supply chain process; recording and storing process parameters and time stamps of tracking components through materials and the manufacturing life cycle for digital twins	[58]
Asset Management	Study of the implications of blockchain and shared ledger technologies to improve trust and cooperation within member states of the safeguard system for the IAEA. This includes proposed applications, such as tracking shipments, as well as proposed nomenclature and technology assessment frameworks.	[59]
Asset Management	Development and demonstration of blockchain-based supply chain security, life-cycle monitoring, and real-time auditing on a lab-scaled power generation system	[63]
Asset Management	Applications of keyless signature blockchain infrastructure in cybersecurity	[129]
Asset Management	Use of blockchain technology for nuclear safeguard applications	[130]
Asset Management	Identification of nonproliferation safeguard use cases that would benefit from blockchain	[131]
Asset Management	Exploration of the benefits of blockchain technology in a joint technology development and transfer agreement use case within the context of nuclear proliferation	[132]
Asset Management	Development of a transit matching blockchain prototype	[133]
Asset Management	A summary of potential blockchain R&D in national security applications based on research activities done at the Stimson Center, the Stanley Center for Peace and Security, and Pacific Northwest National Laboratory	[134]
Asset Management	Assessment of potential blockchain use case applications in safeguards using an analytical framework	[135]
Asset Management	Exploratory study to understand how blockchain could be applied to enhance the security of nuclear material, technologies, and facilities	[136]
Asset Management	Development and demonstration of a blockchain-based cyber supply chain provenance for energy delivery systems	[137]
Asset Management	Implementing a blockchain-based supply chain provenance to manage the supply chain information of bulk electric system operations in energy delivery systems	[138]
Authenticity and Device Integrity	Confirming the provenance and authentication of IAEA safeguard equipment using anomaly detection of data stored in DLTs	[139]
Software Patch Management	Applications of the blockchain patch management framework, including the process from patch creation to installation, and mapping the framework to CIP-010.	[140]

Table 12. Blockchain-based demonstration projects conducted by U.S. utilities within the Supply Chain Management domain.

Use Case Application	Blockchain/DLT Scope	References
Asset Management	A collaborative launched by VIA, Hawaiian Electric, and Vector to improve predictive maintenance capabilities for transformers. Smart contracts housed on blockchain provide access control and user authentication for off-chain, artificial intelligence-based analytics software and analysis.	[60]
Authenticity and Device Integrity	This pilot will coordinate EV charging with solar generation to create a local energy market.	[27]

Table 13. Blockchain use cases in the Foundational Blockchain Research domain.

Use Case Application	Blockchain/DLT Scope	References
Network Services	R&D scoping analysis that identifies possible R&D opportunities for Oak Ridge National Laboratory in alignment with strategic objectives. Various proposals include biomedical and health data sciences as well as a secure energy grid.	[67]
Network Services	Use of blockchain technologies and DLTs to facilitate secure communications and control for sensors, PLCs, and other network devices	[68]
Storage Services	Decentralized data storage and access as well as self-governing, autonomous operation for Ping End-to-end Reporting (PingER) internet performance monitoring data	[70]
Storage Services	Store transactions from shared relational databases in blockchain data structures to increase trust among users and verification of the data	[71]
Storage Services	Development activities to develop a cyber-secure, open-source, cloud-based solution for sharing sensitive electric grid infrastructure data	[141]
Policy/Regulations/ Fundamental Blockchain	Engagement with IEEE P2418.5 activities that focus on energy standards development pertaining to blockchain's use in energy systems, including cybersecurity, interoperability, energy markets, and other application areas within the broad power and energy umbrella	[142]
Fundamental Blockchain	Use of a testing framework for evaluating blockchain performance	[73]
Fundamental Blockchain	Development of the detailed design and demonstration of a unified testing platform that has interoperability to support a wide variety of blockchains	[63,74]
Fundamental Blockchain	Assessment of blockchain platform performance, including Hyperledger Fabric, in terms of throughput, latency, and scalability	[143]
Fundamental Blockchain	Improving blockchain protocol for security with machine learning in addition to DLT protocols designed for the IoT setting	[144]
Fundamental Blockchain	Evaluation of the impacts of blockchain on emergency supply allocation and management using the evolutionary game model	[145]

Table 13. *Cont.*

Use Case Application	Blockchain/DLT Scope	References
Fundamental Blockchain	Qualitative analysis of the performance of the cryptocurrency discussion spread on Reddit	[146]
Fundamental Blockchain	Examine the public blockchain of cryptocurrency transactions to find patterns that appear to match known patterns of illicit activity and explore the use of this information to understand the existence of exchanges and cross-currency movement.	[147]
Fundamental Blockchain	A collaborative group of companies, universities, and government agencies dedicated to making the Cascadia region a global hub for blockchain development	[148]
Compute Services	Use of blockchain to establish data provenance for cloud-based platforms and services (e.g., computing, storage, application hosting)	[65]
Compute Services	Foundational architecture for data provenance and PoS consensus proposed for cloud-hosted data operations	[66]
Compute Services	Blockchain technology to confirm the provenance and integrity for data produced and used by high-performance computing	[69]
Fundamental Frameworks	Development of a blockchain applicability assessment framework	[72]
Fundamental Frameworks	Established cybersecurity standardization efforts and a framework for DLT-based power and energy applications	[78]
Fundamental Frameworks	Demonstration of a rank-weight methodology to prioritize requirements needed to achieve a sought-after cybersecurity maturity level using the BC2F	[149]

4.1. Blockchain Activities by Energy System Domain

After mapping all tracked blockchain activities in Table 3, the overall engagement of DOE and the U.S. utility sector in each system energy domain can be summarized, as shown in Figure 4. The results were organized clockwise, from the highest engagement domain to the least engagement domain based on the tracked projects.

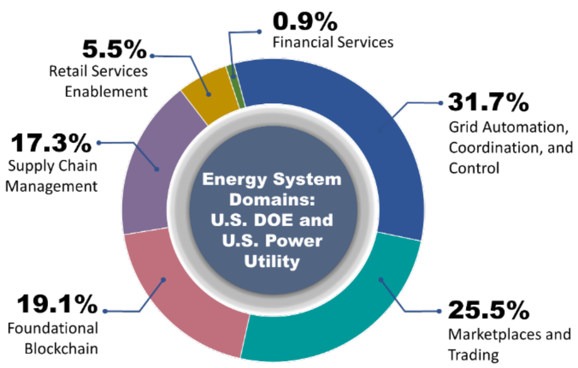

Figure 4. Overall blockchain activities within DOE and the U.S. utility sector by energy system domain.

Ninety-two blockchain activities were identified from this analysis as projects sponsored by DOE, including 56 project grants, whereas 18 blockchain activities were obtained from U.S. utility demonstration projects. EPRI collaborated with energy stakeholders to track many global utility blockchain activities for collaboration and information-sharing. EPRI tracked these 18 U.S. utility-led projects from among 86 total projects worldwide. It was observed that some blockchain projects were designed to address more than one use case application [27,43,63].

Overall, it is recognized that additional blockchain projects exist in the U.S. energy sector more broadly, but they might not be considered for this evaluation of blockchain activity in the United States [13]. So, the total number of blockchain activities tracked in this work might not represent all blockchain publications and activities in the United States that have been performed to date.

Contributions from DOE and the U.S. utility sector in each energy system domain are compared in Figure 5. It is clearly shown that the use cases that were mostly explored by DOE focused on *Grid Automation, Coordination, and Control*, whereas the U.S. power utilities paid more attention to blockchain testing and development within the *Marketplaces and Trading* and *Retail Services Enablement* domains. As expected, all projects classified into *Foundational Blockchain Research* were completely dominated by DOE because the existing effort considered more research-agnostic, groundbreaking work, including basic exploration of blockchain usage and characterization. Surprisingly, among the 18 industry projects identified in this work, none could be mapped to the *Financial Services* domain as defined within this paper. In general, all DOE-sponsored projects were spread among six energy system domains except for the effort within the *Retail Services Enablement* and *Financial Services* domains, which both consist of only one project, as shown in Figure 5. In summary, more projects that involved interactions between service providers and customers were led by the U.S. power utilities.

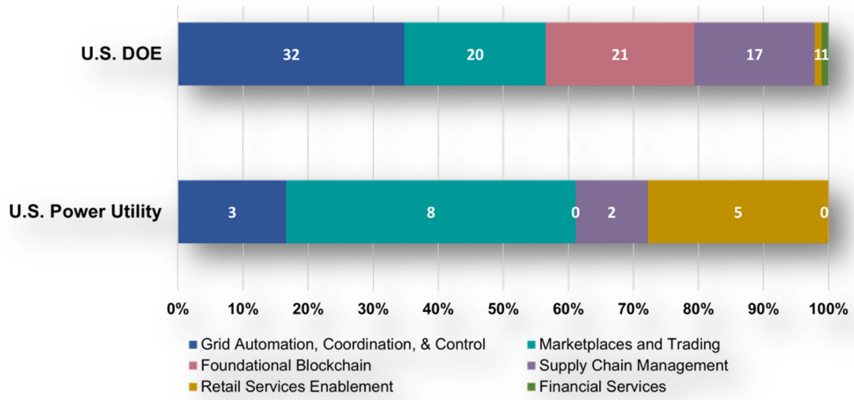

Figure 5. Overall DOE and the U.S. utility contributions by energy system domain.

4.1.1. Grid Automation, Coordination, and Control

Based on our assessment, *Grid Automation, Coordination, and Control* (31.8%) was the most actively pursued area. As shown in Table 3, nine potential use cases were selected to cover potential blockchain applicability in coordination and control, which can include smart sensors, IoT devices, smart buildings, EVs, network monitoring, and data logging. In general, the activities within this domain were quite evenly distributed among the selected use cases. The top two leading scopes were around *DER Coordination and Control* and *Dynamic Controls*, with eight and seven activities, respectively. Currently, existing projects have not yet focused on *Black-Start*, even though it was selected as a promising application by the power industry through a survey conducted by DOE [150]. The rank of the nine use case applications, from the most actively explored to the least actively explored, is shown in Figure 6.

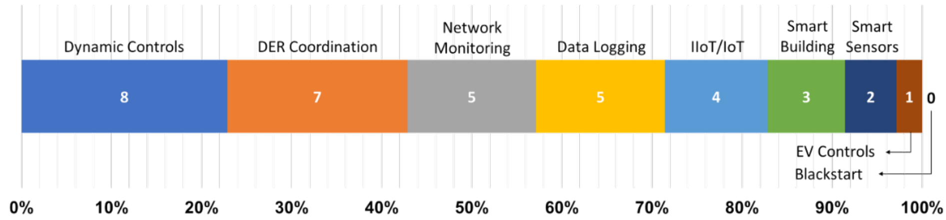

Figure 6. Use case applications in the Grid Automation, Coordination, and Control domain.

4.1.2. Marketplaces and Trading

As shown in Figure 7, the *Marketplaces and Trading* domain consists of five potential use cases. Overall, the existing and ongoing blockchain projects contributed approximately 25.5% to this domain (Figure 4). As expected, most blockchain studies centered on *DER—Transactive Energy Management*, with a 78.6% contribution, compared to the rest of the use cases, as shown in Figure 7. This progress seems to align with an increasing number of DER infrastructures worldwide. Management of energy distributed systems is becoming increasingly challenging. Blockchain technologies have been experimented with to help provide solutions to many issues related to system interfacing and the communications of complex system networks, including data collection, storage, and security. Meanwhile, our analysis indicated that only a few studies focused on exploring the benefits of blockchain for the green certificates trading, emissions credits, and wholesale energy. From the surveyed publications, little to no effort was observed in developing strategies for the *Bidding/Settlement* domain using only blockchain; however, it was expected that this blockchain use case might not be treated as a major activity by itself but instead, is incorporated into other applications, such as in *DER—Transactive Energy Management*.

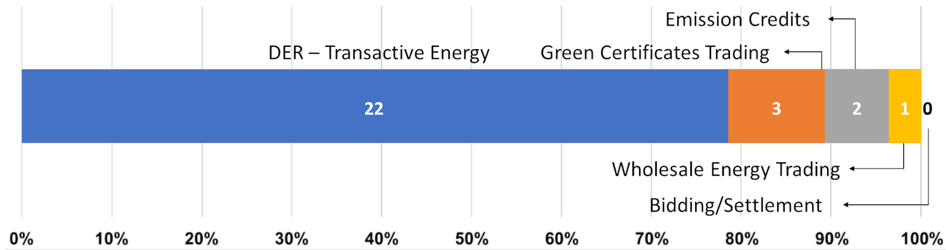

Figure 7. Use case applications in the Marketplaces and Trading domain.

4.1.3. Foundational Blockchain Research

Of the six use case applications proposed for the *Foundational Blockchain Research* domain, shown in Figure 8, nine blockchain projects identified in our literature review were able to be grouped here (42.9%). These studies mostly emphasized blockchain performance evaluation and functionality improvement. Meanwhile, other activities spanned from developing a fundamental framework and improving services for storage, to blockchain compute, to the network. Within the DOE-sponsored projects, only one project was found that was associated with *Policy/Regulations*.

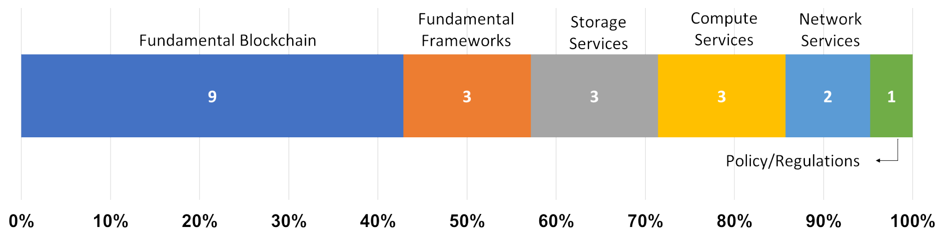

Figure 8. Use case applications in the Foundational Blockchain Research domain.

4.1.4. Supply Chain Management

Supply Chain Management (17.3%) was among the third most associated research applications found from the selected literature in this work. There were at least 19 different activities within DOE and the U.S. power utilities that explored the use of blockchain to tackle some issues in *Asset Management*, *Authenticity and Device Integrity*, and *Software Patch Management*, as summarized in Figure 9. A significant number of projects classified within this *Supply Chain Management* domain primarily focused on *Asset Management*, with approximately 84.2% tracked activities; however, there was no study associated with applicability in *System License Validation* based on our assessment period until Q2 2022.

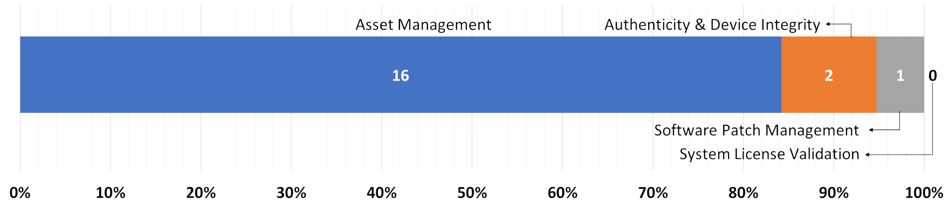

Figure 9. Use case applications in the Supply Chain Management domain.

4.1.5. Retail Services Enablement

Six of 110 total blockchain activities tracked in this work were assessed as *Retail Services Enablement*, which represents 5.5% of the total categorization. The level of engagement in applications within this domain was evenly distributed among three use cases: *Green Certificates*, *EV—Smart Driving Rewards/Insurance*, and *EV—Smart Contracts for Renting, Leasing, and Purchase*, as shown in Figure 10. Meanwhile, no activity addressed *Billing Services* or *Regulation Compliance and Auditing* up to the period of assessment.

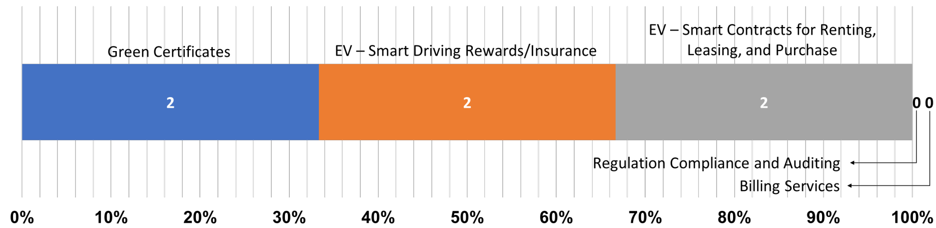

Figure 10. Use case applications in the Retail Services Enablement domain.

4.1.6. Financial Services

Overall, only one blockchain project sponsored by DOE was mapped to the *Financial Services* domain, which is statistically not very significant. This accounts for only approximately 0.9% of the total activities. Other activities that could be grouped into this category were not able to be tracked in our evaluation or might not be publicly available. One key area in the *Financial Services* domain centers on cryptocurrencies, such as Bitcoin and Litecoin. A key recommendation here is for DOE to support research and analysis focused on energy consumption associated with consensus mechanisms for cryptocurrencies. Using PoW as an example, methodologies to estimate the amount of energy being consumed could be a potential research area.

4.2. Blockchain Activities by Blockchain Properties

The second dimension of the proposed 2-D categorization framework shown in Table 3 enabled mapping the surveyed blockchain DOE-sponsored projects and industry demonstration projects to the blockchain properties. This analysis could aid in understanding why the application was proposed and the limitation of the application if it existed. Only the top two blockchain properties used in the projects were mapped in Table 3 so that the purpose of the application could be more objectively assessed to meet the goal of this work; however, an exception was given to the *Foundational Blockchain Research* domain, particularly for use cases related to *Fundamental Blockchain*, *Fundamental Frameworks*, and *Policy/Regulations.* These three use case applications addressed blockchain-agnostic cases, in which all blockchain technologies could be applicable; thus, the breakdown shown in Figure 11 does not consider the activities that were mapped to these three categories.

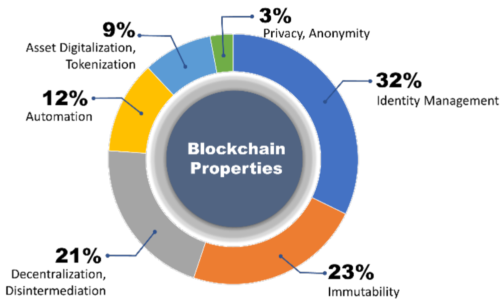

Figure 11. Blockchain activities by the top two important properties.

As shown in Figure 11, *Identity Management* (32%) was the most frequent blockchain property being leveraged compared to the five other properties considered in this work. Intuitively, this blockchain property is crucial to ensure the security of digital solutions in the real world. This property was mostly used to record and attest to metadata for physical assets, digital information, and authenticating entities in supply chain management. As shown in Figure 12, most blockchain activities that applied *Identity Management* were grouped in the *Supply Chain Management* domain. This property could be essential for managing DER assets, control, and coordination as well as transactive energy markets and trading, depending on the goal of the application, because this property can represent singular identities for data, equipment/applications, organizations, and individual participants.

Immutability (23%) was observed as the second most favorable property that was considered in DOE research and the surveyed industry projects (Figure 11). Most cases grouped in the *Supply Chain Management* as shown in Figure 12 focused on the safeguard of nuclear assets and technologies, such that *Immutability* is critical for maintaining security. Similarly, this property was considered in the *Foundational Blockchain Research* domain, which includes applications for network, compute, and storage services. It was expected that this property was leveraged to evaluate the applicability of blockchain in these applications as a basic requirement; note that all these studies were at a low TRL level. Identical to *Identity Management*, *the Immutability* property was predominantly used to support DOE-sponsored activities that spanned across all six energy system domains.

On the other hand, the applicability of the *Decentralization and/or Disintermediation* (21%) properties were most explored in DER-associated applications, such as *DER—Transactive Energy Management*, *DER Coordination and Control*, and *Dynamic Controls*, as mapped in Table 3. This property is mainly associated with the goal to facilitate transactions in distributed infrastructure without trusted third parties, which currently exist in centralized energy transaction systems. This was an essential blockchain feature that could help improve data acquisition and control systems to efficiently communicate with increasingly complex DER networks and smart sensors, IoT devices, and behind-the-meter systems. The same requirement was also expected for energy trading platforms to provide trusted and effective marketplaces for DER services. *Decentralization and/or Disintermediation* was also considered among the three blockchain properties that were deployed for activities in the *Foundational Blockchain Research* for early-stage testing, including *Identity Management* and *Immutability* properties.

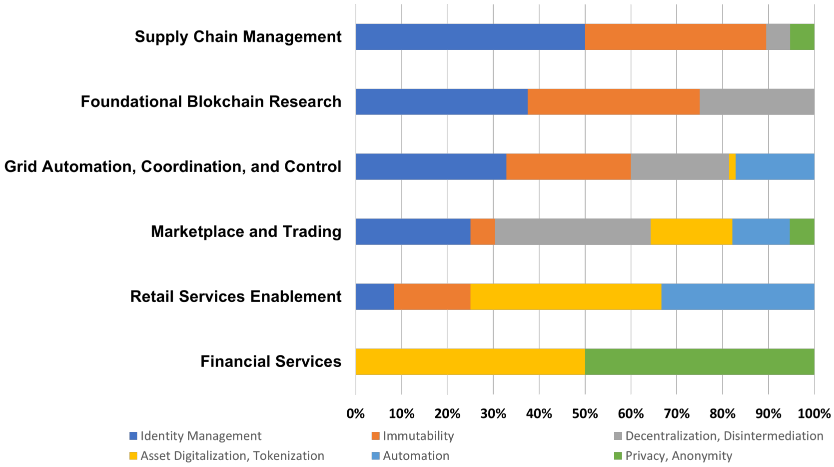

Figure 12. Blockchain properties by energy system domain.

The other three properties—*Asset Digitization and/or Tokenization*, *Automation*, and *Privacy and/or Anonymity*—were not prioritized in the current application testing, especially within the *Foundational Blockchain Research* domain. Intuitively, these properties would be applied after the detailed blockchain design was developed, which is usually not considered within the scope of *Foundational Blockchain Research*. Overall, properties such as *Automation* and *Asset Digitization* were more important for the applications that are more mature and have higher TRLs for industry deployment, such as in *DER—Transactive Energy Market* and *Controls*. As shown in Figure 13, *Automation* and *Asset Digitization* were primarily leveraged by the power industry to finalize the quality of the proposed applications for trust improvement and longevity.

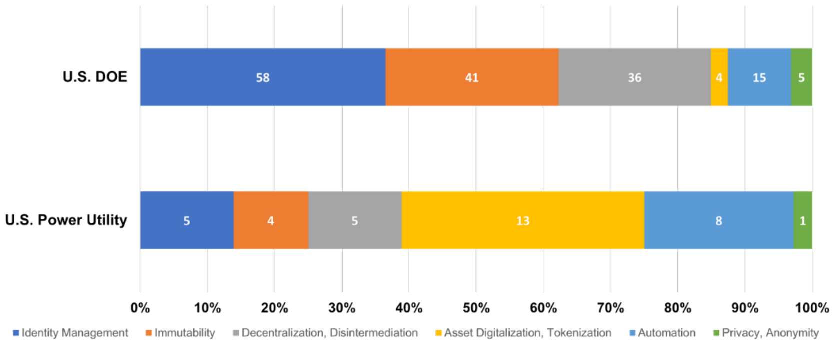

Figure 13. Blockchain properties by DOE and U.S. power utility.

5. Conclusions

This work established a new, 2-D blockchain categorization framework that is based on (1) six energy system domains and 30 potential use case applications in the first dimension; and (2) six inherent properties of blockchain that could be leveraged for a given use case activity in the second dimension. An assessment was conducted of a total 110 blockchain activities that considered DOE-sponsored research and 18 U.S. power industry demonstration projects. All these projects were successfully mapped into the developed categorization framework. By taking this 2-D, matrixed approach, research activities and investments can be easily observed in an intuitive fashion that allows for quick analysis and evaluation of a respective R&D portfolio overall.

5.1. Energy System Domain

The mapping results revealed that participation in testing blockchain applicability in the six energy system domains can be ranked from the highest overall engagement—in *Grid Automation, Coordination, and Control* (31.8%), *Marketplaces and Trading* (25.5%), *Foundational Blockchain Research* (19.1%), *Supply Chain Management* (17.3%), *Retail Services Enablement* (5.5%)—to the least engaged domain, in *Financial Services* (0.9%).

This study revealed that in energy domains where there was relatively higher industry participation and little to no DOE investment, there was a strong trend toward consumer-facing use cases within the *Retail Services Enablement* domain, with 83% contribution from the power industry vs. 17% from DOE. Conversely, it was observed that the domain that featured more DOE activity with relatively negligeable industry participation was *Foundational Blockchain Research*. This was consistent because foundational research is use case agnostic, with an emphasis on early-stage, proof of concept investigations.

Overall, DOE participated in the exploration of blockchain potential use in all six energy system domains, but scarce activities were still observed in *Retail Services Enablement* and *Financial Services* based on the number of tracked projects. For industry, research was generally tied to a specific use case application such that a clear ROI would be attained if successful.

In comparing the percentage of effort focused on each energy system domain by both DOE and industry researchers, only the *Marketplaces and Trading* and *Retail Services Enablement* domains stood out as being favored by industry researchers over DOE-sponsored research by a factor greater than 2 (2.3 and 2.6, respectively).

5.2. Use Case Application

Our detailed analysis of specific use cases in each energy domain shows that the level of interest to address blockchain applicability within the *Grid Automation, Coordination, and Control* and the *Retail Services Enablement* domains was relatively equal across the proposed use cases. In contrast, *DER—Transactive Energy Management* (78.6%), *Asset Management* (84.2%), and *Fundamental Blockchain* (42.9%) were the three leading use case applications, which, respectively, represent the *Marketplaces and Trading*, *Supply Chain Management*, and the *Foundational Blockchain Research* domains.

Note that use case applications and energy system domains with little to no DOE-funded R&D activity pose a compelling opportunity to explore new research areas and provide much-needed leadership, such as in *Black-Start, Bidding/Settlement*, *System License Validation*, *Regulation Compliance and Auditing*, *Billing Services*, and *Financial Services*. During the assessment period, either no or very limited activities could be categorized under these applications even though these categories were identified as promising applications based on discussions with industry partners in the BLOSEM project. These use case applications might need more attention for future blockchain research and testing.

5.3. Blockchain Properties

It was also observed that the top three blockchain properties that have been leveraged by the studies identified within this work were *Identity Management*, *Immutability*, and *Decentralization*, *Disintermediation*. Meanwhile, *Automation* and *Asset Digitization/Tokenization* were identified as lower priorities in most activities in general except in industry applications that involved *Retail Services Enablement* and *Marketplaces and Trading*. *Automation*, however, has gained interest from DOE, primarily within *Marketplaces and Trading* and the *Grid Automation*, *Coordination*, and *Control*, through the deployment of smart contracts. *Privacy and/or Anonymity* was classified as the least frequent property being leveraged by all activities in general.

In comparing the interest in blockchain properties between DOE-sponsored research and industry research, the largest discrepancies appeared in *Asset Digitization/Tokenization* and *Automation*. These two properties represented the greatest interest in industry research and the least interest in DOE-sponsored research. Proportionally, the industry effort (36%) in *Asset Digitization/Tokenization* was 14 times more intensive than the DOE-sponsored effort (3%). The research effort in *Automation* by industry (22%) was 2.4 times more intensive than the DOE-sponsored effort (9%).

Overall, quantification of research efforts by DOE and industry sponsors through mapping the energy system domains and blockchain properties provided insight into opportunities for expanding research efforts to improve energy sector performance in a carbon-constrained world by using blockchain technologies.

6. Future Work

Participation and investment from DOE and industry are essential for continuous improvement in blockchain technologies based on current operations and practices. Future work will have to determine the needs and challenges to accelerate the adoption of decentralized technologies within the energy sector. Follow up studies should guide resources to determine the near-term use cases prioritization to address industrial needs and how future DOE R&D can support to advance solutions to the commercialization stage. One main area that can potentially help to accelerate the deployment of DLT is through development of testing and validation platforms. These platforms should be constructed for blockchain-agnostic assessment, which can facilitate the maturing any of proposed DLT-based solution at various technology readiness levels. Additionally, there is a need for systematically evaluating the technology readiness levels of various development projects, which is an essential step towards identify solutions that are ready to transition into the commercialization phase.

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